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TEN YEARS OF

HUMAN VIBRATION RESEARCH

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THE BOEING COMPANY
WICHITA DIVISION - WICHITA, KANSAS, 67210

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TEN YEARS OF HUMAN VIBRATION RESEARCH

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Research Accomplished Under
Office of Naval Research
Contract Nonr-2994(00)

"Research On
Low Frequency Vibration Effects
On Human Performance"

Principal Investigator
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HUMAN FACTORS STAFF

THE BOEING COMPANY
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ABSTRACT

This report reviews ten years of research in whole-body, low frequency vertical vibration supported by both the Office of Naval Research and The Boeing Company, Wichita Division. The results of twelve studies are presented, five in which the objective was to define and quantify human subjective reactions to vibration and seven in which vibration was a baseline condition for evaluation of sensory-motor task performance.

The subjective response studies presented test subjects the task of identifying acceleration levels which would qualify for the verbal labels "perceptible", "mildly annoying", "extremely annoying", and "alarming". Fifteen vibration frequencies ranging from 1 Hz to 27 Hz were studied in this manner. The acceleration levels so identified are comparable to those reported by other investigators in vibration research; and where major differences were noted, they are discussed in the report. Generally, the subjective response studies produced reliable and consistent findings both within and among themselves.

Consistency of results in the subjective reaction studies is in contrast to the variability in results of the sensory-motor effects studies. The general finding was that tracking performance and speed and accuracy of control movements are degraded under vibration. Similarly, reading of smaller numerals is degraded by vibration, while speech intelligibility and auditory performance are not significantly degraded under the conditions of the tests.

Physical effects of vibration are discussed in terms of the relationship between frequency of vibration and body sensation.

Research areas requiring further study are introduced and directions in vibration research for the future are suggested.

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FIGURES

FIGURES (Continued)

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1.0 INTRODUCTION

This report summarizes a ten-year program in the study of the effects of whole body low-frequency vertical vibration on the human. Industry interest in vibration was accelerated when the realities of the Cold War elicited changes in strategic bombardment operational requirements. The emerging emphasis on low level, high-speed penetration placed increased demands on aircrews; for, associated with a terrain avoidance mission there would be visual problems, vigilance and reaction time problems, and, of course, problems associated with ride and handling qualities. Basic to all these problem areas was the shaking of the crew member resulting from turbulent air encountered during low level high speed penetration. Questions as to the role of vibration in performance degradation (and ultimately mission accomplishment) and questions regarding aircrew tolerance to vibration began to emerge.

A preliminary U.S. Air Force supported study of aircrew tolerance to low frequency whole-body vertical vibration (Gorrill and Snyder, 1957) ultimately led to support of a research program by the Office of Naval Research (Contract Nonr 2994-00) and, although the red and white lighting study (Morris, 1966) was Boeing funded, the bulk of the studies reported here were supported by the Office of Naval Research.

The vibration research ~~has been~~ organized around three main interest areas, 1) subjective reaction to vibration, 2) effects of vibration on sensory and motor processes, and 3) physical effects of vibration. Before presenting detailed summaries of the major studies in our program, the report briefly highlights these main interest areas, introducing methodological aspects, mentioning general results, and suggesting how the various aspects of the program fit together.

a. Subjective reactions to vibration: Four studies (Parks and Snyder, 1961; Chaney, 1964, 1965; and Brumaghim, 1967) required the volunteer test subject to experience gradually increasing vertical vibration intensity and report the acceleration levels at which he judged the vibration amplitudes to be perceptible, mildly annoying, extremely annoying, and alarming. These levels came to be known as the "subjective levels." One frequency at a time was investigated, and amplitude was controlled by the subject in the later studies. Under these conditions both sinusoidal and random vibrations were studied, and subjects were run in the standing as well as the seated position. In a recent study, a second vibration frequency was superposed on a fixed "basic" frequency. Here the subjective judgments were made on the variable superposed frequency. The subjects were instructed to attend only to the variable frequency in making their ratings. In all cases vibration frequency in these studies has not exceeded 27 Hertz (Hz: cycles per second) and the resultant acceleration levels have been limited to a maximum of 3.0 g.

The results of the subjective judgment studies identified a group of subjective reaction curves (perceptible, mildly annoying, extremely annoying and alarming) which were observed to be fairly reliable as this part of the program proceeded from one study to the next.

b. Effects of vertical vibration on motor and sensory performance: Compensatory tracking performance (Parks, 1960; Chaney and Parks, 1964a; and Morris, 1966) and knob, lever and thumbwheel operation (Chaney and Parks, 1964b) under conditions of vibration have been investigated in a format which involved varying control forces, subject workload, and severity of vibration. Here the general result is that tracking performance and speed and accuracy of control movements are degraded under vibration conditions, with vertical tracking performance more susceptible to the impact of vertical vibration than performance of a horizontal tracking task. Studies which are more sensory-performance oriented have included effects of vibration on speech and hearing (Teare, 1963), visual performance (Teare and Parks, 1963) visual-motor performance (Chaney and Parks. 1964a), and numeral reading with red and white lighting (Morris, 1966).

In these investigations, the vibration levels usually corresponded to the severity levels obtained in the earlier subjective judgment studies (Parks and Snyder, 1961). The results of the sensory processes group of studies are harder to summarize since sensory performance variability has been high in the test subjects and individual differences seem to interact with task complexity. A few preliminary results might be mentioned here:

Within the limits of vibration conditions (0-27 Hz, 0-3 g), hearing decrement in the shaking subject appears to be of such small magnitude as to be of no operational significance; speech intelligibility (although not given a thorough test) does not seem to be markedly degraded; and counter reading performance is degraded under vibration (12-23 Hz) for very small numerals (less than 12 min. of arc visual angle, or 1/8 inch high) at the 28 inch viewing distance.

In the most complex sensory performance study of the group (Morris, 1966), the conditions varied were illumination color (red or white), illumination level (1.00, 0.10 and 0.01 foot-Lambert) and vibration level (0, random, 6 Hz and 16 Hz sinusoidal). Both numeral reading and compensatory tracking were assessed. The results do not lend themselves to summarization and will be discussed in sections 4.2.2, 4.2.3 and 4.2.4.

c. Physical effects of vibration: Qualitative reactions to vibration, such as abdominal pain, chest pain, backache, vision blurring, gas emission, swallowing difficulty, and the like, have been common enough to permit tentative correlation with vibration frequency, and these data are discussed in section 5.0.

d. <u>Medical surveillance</u>: All volunteer subjects were medically evaluated and approved for vibration testing and were monitored during the vibration tests. Additional follow-on medical evaluations were also performed. It became routine to conduct urinalyses, take blood pressure, pulse, respiration, and temperature measures before and after each subject's vibration runs, and to record and monitor electrocardiograms during vibration runs. In general, these measures were taken in the interests of safety and did not lend themselves to differential analysis.

2.0 VIBRATION FACILITY AND RESEARCH METHODOLOGY

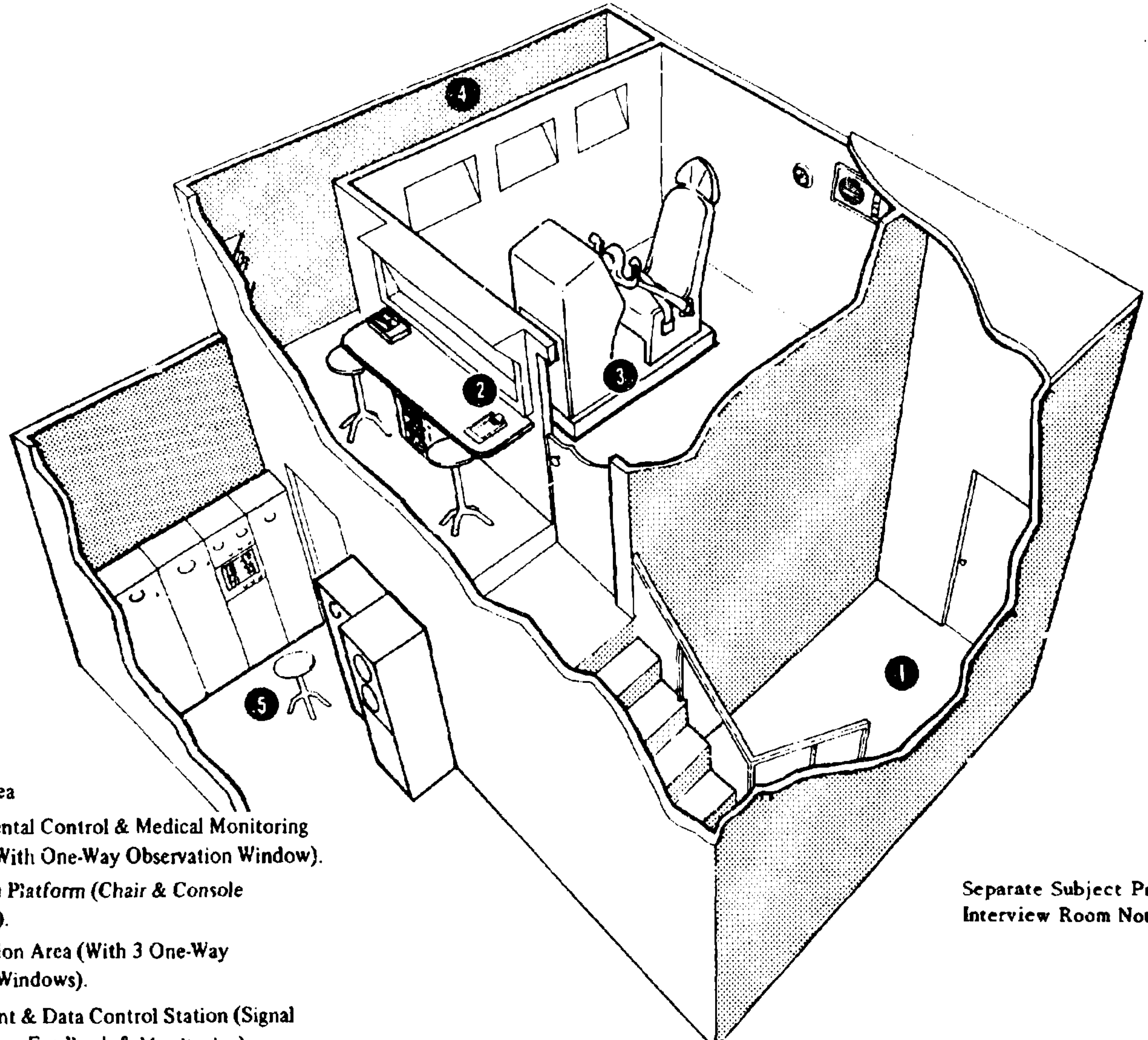
2.1 Vibration Facility

The Boeing Vibration Facility (Figure 2-1), which has been described in detail by Beaupeurt (1962) and in a Human Factors Unit brochure (1960) consists of five functionally distinct areas: 1) entrance to the facility; 2) the experimenter's and medical monitor's station; 3) the vibration platform, chair, and console; 4) the observation area; and 5) the equipment operator's station. Pre- and post-test medical checks and subject interviews are conducted in a room near to but separate from the vibration facility.

The subject is visible through one-way vision windows from areas (2) and (4), permitting observers to make detailed records of a test subject's reactions to vibration conditions. Before and after each vibration session, the subject has a brief medical check. Two-way voice communication links are provided between area (2) and areas (3) and (5). An electrocardiagram recorder located in area (2) allows the medical monitor to assess the heart activity of the subject either continuously or intermittently whenever the subject is seated on the vibration platform in area (3). Tape recorders in area (2) can record any verbal communication from the subject or provide masking noise to the test area. The vibration facility is air-conditioned, making it possible to hold facility temperature at about 70°F, while holding relative humidity at 50% ± 10%. The interior of area (3), housing the vibration platform, is painted a dark matte green to reduce the availability of visual cues from stationary surfaces. Further control of extraneous visual cues to motion is achieved through dimming or extinguishing overhead room lights as required.

The heart of the facility is the electrohydraulic system that energizes and controls the vertical vibration input to the subject. The system can presently achieve a double amplitude displacement of 20 inches and can transmit vibration frequencies throughout the range of 1-27 Hz. The vibration table can carry a load of 1000 pounds, including a control/display panel, seat and subject, and faithfully transmit the desired vibration input (Chaney, 1964).

Vibration inputs to the table take the form of sinusoidal, random, or shaped random vibration. Both on-line and taped inputs are used. The output of on-line random signal generators can be filtered to match power spectral density (PSD) curves of selected airplanes. Or, vibrations characteristic of the same PSD curve can be presented to subjects on tape to permit exact duplication of very complex vibration patterns over an entire experiment. Vibration intensity can be controlled by the subject or the equipment operator, as dictated by the test design. These capabilities provide opportunities for studying problems as basic as that of defining subjective reactions to sinusoidal vibrations and as applied as that of measuring tracking performance under simulated high speed, low level flight.



1. Entry Area
2. Experimental Control & Medical Monitoring Station (With One-Way Observation Window).
3. Vibration Platform (Chair & Console Mounted).
4. Observation Area (With 3 One-Way Viewing Windows).
5. Equipment & Data Control Station (Signal Generation, Feedback & Monitoring).

Separate Subject Preparation and Interview Room Not Shown.

BOEING HUMAN VIBRATION FACILITY

Figure 2-1

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The vibration seat configuration is changed according to the purpose of the test. The seat used in most of the vibration tests is rigid and covered with reinforced plywood inserts and a pad of three-quarter inch hard felt. A vertically adjustable 4 x 8 inch (vertical x horizontal) felt covered support is provided near the region of the first lumbar vertebra for the subjective reaction tests. The support helps the subjects to maintain an erect seated position. Subjects are also instructed to sit with their shoulders away from the back of the vibration seat. A felt covered foot rest is provided and is adjustable for each subject to maintain an approximate 110° angle between his upper and lower leg. The torso and the upper leg form a 90° angle; the feet also form a 90° angle with the lower leg. A specially fabricated seat belt is used to restrain the subject in his seat. The belt is adjusted to 30 pounds tension at the start of each vibration session.

2.2 Research Methodology

Research plans and methods have been tailored to the test conditions pertinent to the various studies, but certain major emphases and strategies have been common to all the vibration studies discussed in this report. One emphasis concerns definition of the vibration environment. Experience has shown that measures of peak acceleration, displacement amplitude and frequency are not wholly adequate for defining the impact of vibration on human performance. This is especially true when such measures represent only the commands given to the vibration apparatus rather than actual dynamic outputs of the system transmitted to the subject (person experiencing vibration).

Thus it is essential to know the output waveform of the shaker as well as the responses of the human (both physical and psychological) to the shaker output. Only when accurate control, measurement, and reporting of these critical factors are accomplished can vibration tests be compared meaningfully.

The decision to concentrate on single rather than multiple and complex vibration frequencies exemplifies the research strategy which has guided most of the Boeing studies. It is possible to duplicate some of the complex waveforms encountered in operational environments, but it is unlikely that any one complex vibration pattern would represent all environments involving shake (or even a significant portion of any one such environment). Thus, generality of results would be limited, and added to this problem would be those of quantifying, reproducing and controlling complex vibrations were they employed.

The question remains regarding the feasibility of relating results obtained under conditions of single frequency, sinusoidal vertical vibration to human performance in a more realistic environment. Parks (1961) approached the problem directly in examining the possibility of formulating a mathematical transfer function to permit reliable extrapolation of laboratory results to operational conditions. The vibration conditions used were a simulated power spectral density (PSD) curve having greatest relative power at the frequencies of 0.75 and 2.5 Hz. Subjects were asked to perform any one of three tasks at different times during the vibration sessions. The tasks were a vertical tracking task in which display movements followed control inputs after a two second delay, a horizontal tracking task with no feedback delay, and a reaction time task. The measures used that might enter into the transfer function were subjective judgments of vibration severity, equal mean vibration amplitude and equal root mean square (RMS) amplitude power. The vibration conditions were equated on the basis of these three measures. Parks found the equal RMS amplitude power measure to be a parameter "... with comparable effects on human performance for different vibration conditions ..."

Quite obviously, although vibration input is the major variable affecting reaction to vibration, there are additional factors influencing a test subject's reaction. One such factor is the subject's test environment. The conditions under which the subject experiences vibration should be controlled and attempts should be made to eliminate irrelevant cues that might otherwise influence his reactions to vibration. Of first concern, of course, is the control and specification of the variables under study - the illumination and size of displays, the size and nature of display markings, and their position relative to the subject. In studies of motor performance under vibration, these variables would include the size, shape, nature and locations of operator controls.

Other elements of the vibration test environment are the stimulus characteristics of the test compartment itself and factors affecting the subject's posture. Instructions are likewise very important. These elements are often less well defined than those considered the independent test variables and yet their specification is critical to a valid interpretation of the test results.

3.0 SUBJECTIVE REACTION

3.1 Establishing Baseline Reactions

The original purpose of the vibration program was to study the effects of vibration on human task performance. It was judged necessary to first determine the reactions of human subjects to vibration environments in the absence of any additional task assignment. Decisions had to be made regarding the waveforms, amplitudes, and frequencies of the vibration inputs to be used; and it became clear that determining the test subjects' personal reactions to the inputs was basic to investigations in which a task loading was paired with vibration.

Thus a series of studies was undertaken in which the goal was to scale the severity of vertical vibration by means of exposing human subjects to a variety of vibration frequencies, instructing them to react verbally as the amplitude or the stroke of the vibration table was increased or decreased (i.e., as the g level was increased or decreased at a given frequency). Verbal definitions of severity levels were provided the subjects during briefing or pretraining sessions, and their assignment was to identify the acceleration levels at which the verbal definitions of severity seemed to be appropriate. Early studies were restricted to single frequency vibration inputs with only the displacement amplitude (thus g-level) varied. Each study represented an updated extension of its predecessor, involving technological improvements and producing, presumably, data having greater reliability and generality.

Following completion of the early subjective studies a second research strategy was introduced; namely, the investigation of effects of vibration severity on sensory and motor task performance. Here the severity levels defined in the subjective reaction studies were applied to human subjects working to maintain a compass heading, performing a simulated aircraft pitch-tracking task, or reading digital counters. The relationship between vibration severity and task performance was then determined.

3.2 Subjective Reaction Studies

Since the sensory-motor task studies are discussed in a subsequent section, only the subjective reaction studies will be dealt with here. For the sake of clarity, and to illustrate the way one study led to the next, the four relevant studies will be dealt with in chronological order.

3.2.1 Acceleration Levels Identified

The first subjective reaction study was that of Gorrill and Snyder (1957), whose subjects, all aircrewmen, were asked to identify acceleration levels they considered to be "Threshold of Perception" (just barely noticeable), "Definitely Perceptible," "Annoying," "Maximum Tolerable for Continuous Operation," and "Intolerable." Reference points for these labels were to be drawn from the subjects own flight experiences (an instruction that was deleted from later studies). The severity levels were established for frequencies of 3, 4, 5, 6, 8, 10, 15, and 30 cycles per second (Hz). This first study included a tracking task for the subjects, but data were not collected on the task while the subjective reactions were obtained.

The results were expressed in terms of the acceleration levels (g) associated with the subjects' identification of the five severity levels listed above. In general, the correspondence between g levels and subjective definitions was as expected: the more menacing the verbal label, the higher the corresponding g.

Subjective Reaction	Approximate Acceleration Range (g)*
Threshold of Perception	.01 - .02 g
Definitely Perceptible	.02 - .08 g
Annoying	.10 - .25 g
Max. Tolerable for Continuous Oper.	.40 - .80 g
Intolerable	.70 - 1.50 g

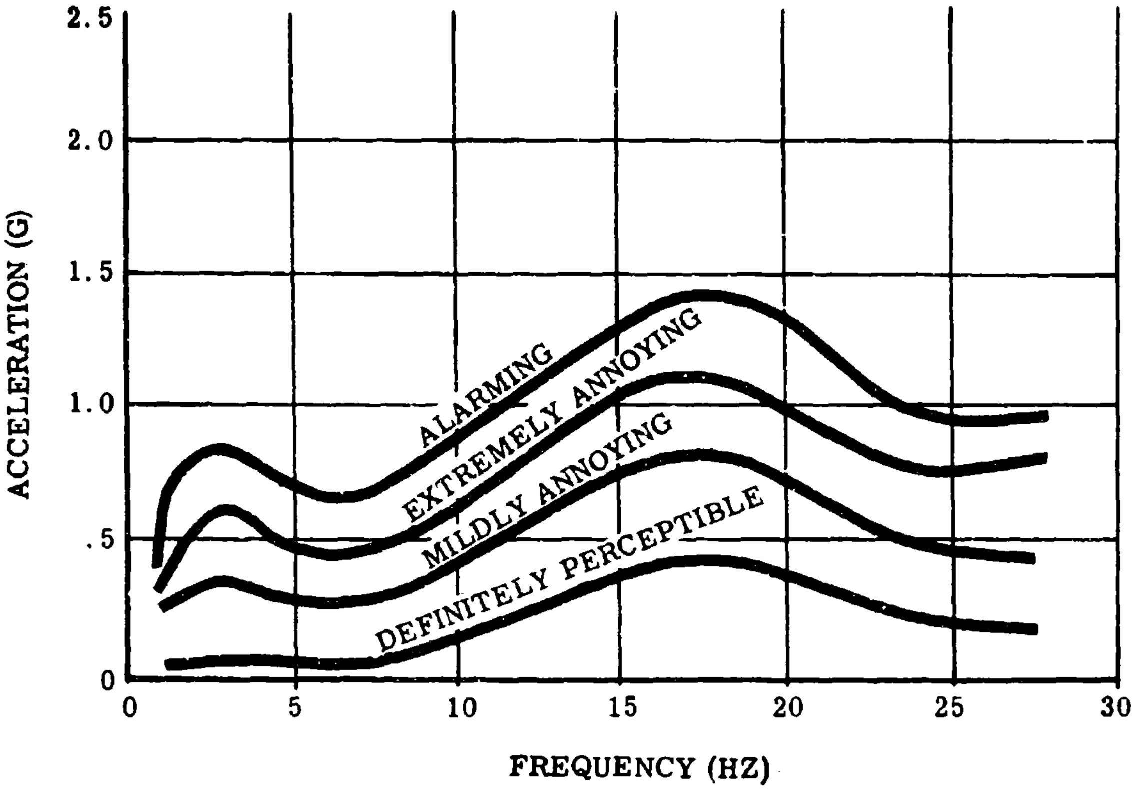
The Gorrill and Snyder study (1957) highlighted the unique role of vibration frequencies in the range of 3-10 Hz in causing discomfort in the subjects. The subjective reaction curves show a drop in acceleration (i.e., lower tolerance) for those frequencies (Figure 3-1), implying that the test subjects were more sensitive to frequencies in the 3-10 Hz range than to frequencies either higher or lower. This dip in subjective reaction curves was to be observed in the Boeing vibration studies which followed Gorrill and Snyder, and is thought to be associated with internal organ or other body mass resonance.

3.2.2 Replication and Refinement

The second subjective reaction study (Parks and Snyder, 1961) featured improved experimental controls, such as a masking out of mechanical noise, reduction of visual cues to motion, and increased rigidity of the subjects' chair. In addition, a new array of subjective reaction labels was introduced. These were "Definitely Perceptible," "Mildly Annoying," "Extremely Annoying," and "Alarming." These labels became standard in subsequent studies.

Parks and Snyder studied frequencies of 1, 1-½, 2, 3, 4, 5. 6, 8, 10, 12, 16, 18, 20, 23, and 27 Hz, and, as before, slowly increased amplitude at one frequency until the subject identified the relevant severity level. The study produced a set of subjective reaction curves across frequencies which were similar to those of the earlier study in terms of what subjective reactions went with what acceleration levels. But the role of vibration frequency in determining subjective reaction was clarified in the Parks & Snyder experiment (Figure 3-1). The subjects' sensitivity to vibration was greatest at 1 Hz, whatever the severity level he was judging at the moment (an artifact of jerkiness in table motion at this vibration frequency -- eliminated by

* These ranges in acceleration levels illustrate the variations in subjective reactions of the five test subjects across the band of frequencies investigated.



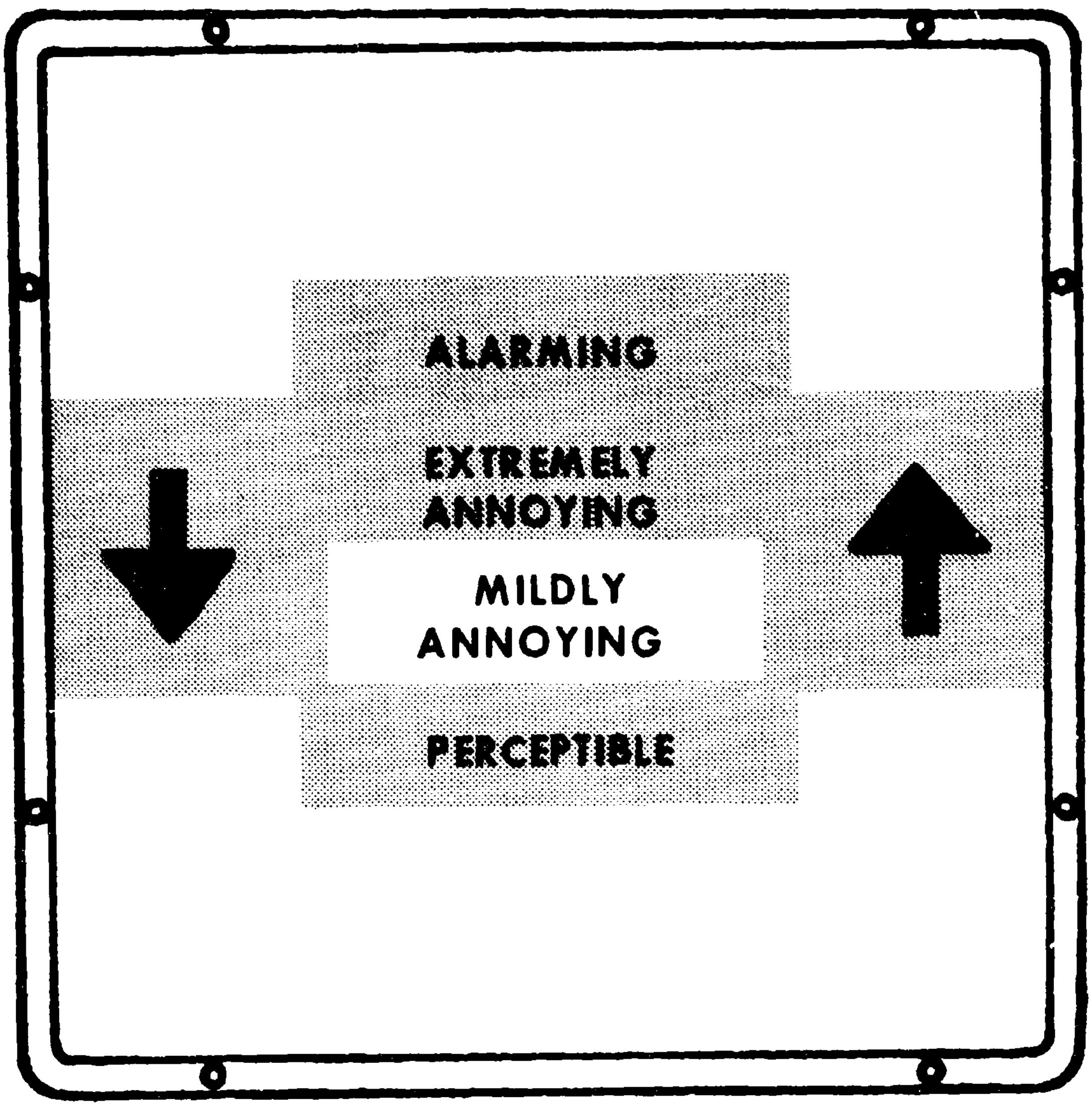
FOUR LEVELS OF VIBRATION (PARKS & SNYDER, 196I)

FIGURE 3-I

later modifications in table guide bearings). Sensitivity then decreased up to 3Hz, and the reaction curves climbed. A sharp increase in sensitivity (and a drop in the reaction curves) occurred with frequencies in the 4-10 Hz range. With frequencies of 10-18 Hz, sensitivity of the subjects declined progressively, and greater acceleration levels were required before a subject would attach a given subjective reaction label to the vibration he experienced. Beyond 18 Hz, sensitivity increased as frequency increased, the acceleration curves dropped, and it was apparent that severity as judged by the subjects was increasing along with frequency (as shown by later studies to be an artifact of sine wave distortion). In summary, it appeared that vibration frequencies in the area of 16-18 Hz could be tolerated up to about 1.0 g before considered alarming, to about .90 g before considered extremely annoying, and to about .70 g before a subject called the vibration annoying. This finding relevant to the 16-18 Hz frequency range was in contrast to the earlier finding (Gorrill and Snyder, 1957) that 16 Hz was a frequency readily called annoying or maximum tolerable by their subjects; and the difference was attributed to the tightening of experimental controls in the second study. A more detailed report of the results of this study is given by Parks (1962).

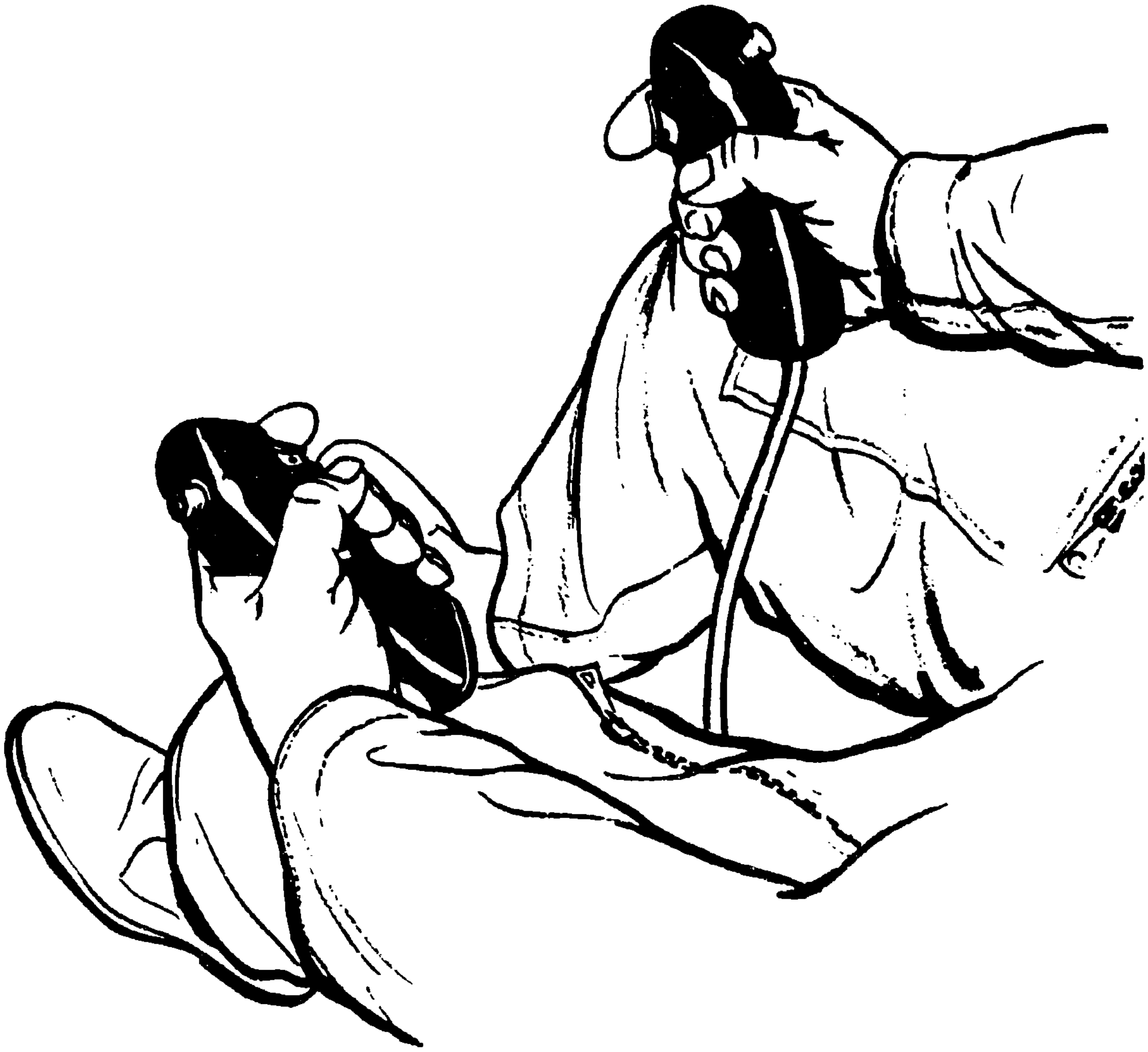
Chaney (1964) further modified the vibration facility by increasing fidelity of the vibration input to the subject and by giving the subject control of the amplitude. The subject could now drive the vibration table, bringing up (or down) the acceleration levels according to his own wishes. A lighted panel (Figure 3-2) told the subject which subjective reaction level he was to define, and he squeezed a hand-held trigger (Figure 3-3) to increase and decrease amplitude (thus g) to the point at which he made his judgment. The frequencies studied were those previously investigated by Parks and Snyder (1961).

Apparently, giving subjects control of amplitude onset (and increasing fidelity of vibration input) had the effect of decreasing their sensitivity to vibration, since Chaney's subjective reaction curves (Figure 3-4) were associated with higher acceleration levels than their counterparts in Parks and Snyder (1961). An exception is Chaney's Definitely Perceptible curve, which is essentially a horizontal line (vibration was perceived when acceleration reached about .05 g for any frequency beyond 5 Hz). The annoying, extremely annoying, and alarming subjective reaction curves showed low points between 5-8 Hz, implying greatest subjective sensitivity to vibration at these frequencies. Beyond these frequencies the reaction curves climb: At frequencies above 8 Hz, greater acceleration levels are required to elicit judgments by the subjects; and, the higher the frequency (up to 27 Hz), the greater the acceleration required. Again, one band of frequencies stood out as especially menacing for the subject: lowest g levels were required to elicit the various subjective reactions when vibration frequencies were in the range of 4-8 Hz. The results of this test have been compared to curves obtained by other researchers (Goldman, 1948; Magid, Coermann and Ziegenruecker, 1960) to give the reader an idea of the relationship among the different studies (Figures 3-5 and 3-6).



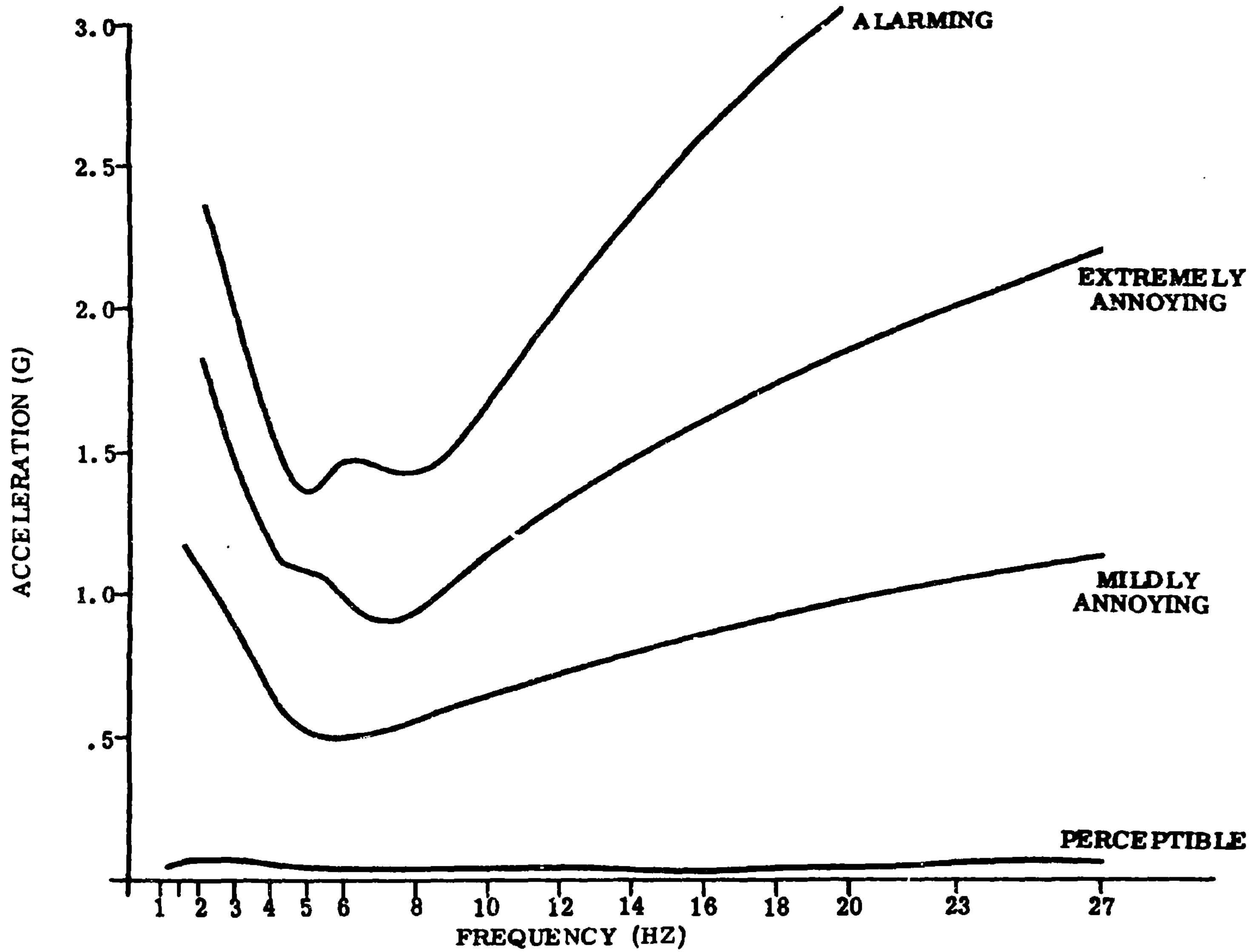
SUBJECT DISPLAY CONSOLE (CHANEY, 1964, 1965)

Figure 3-2



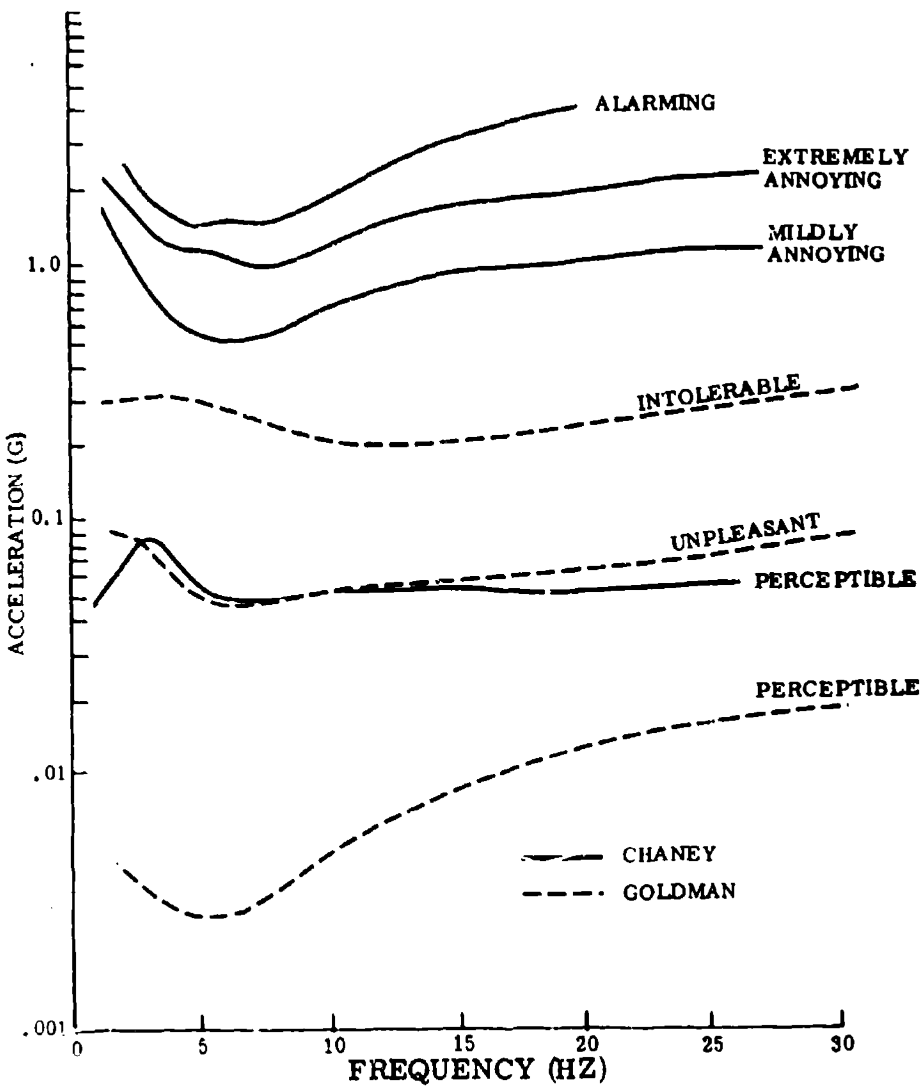
VIBRATION CONTROL HANDLES

FIGURE 3-3



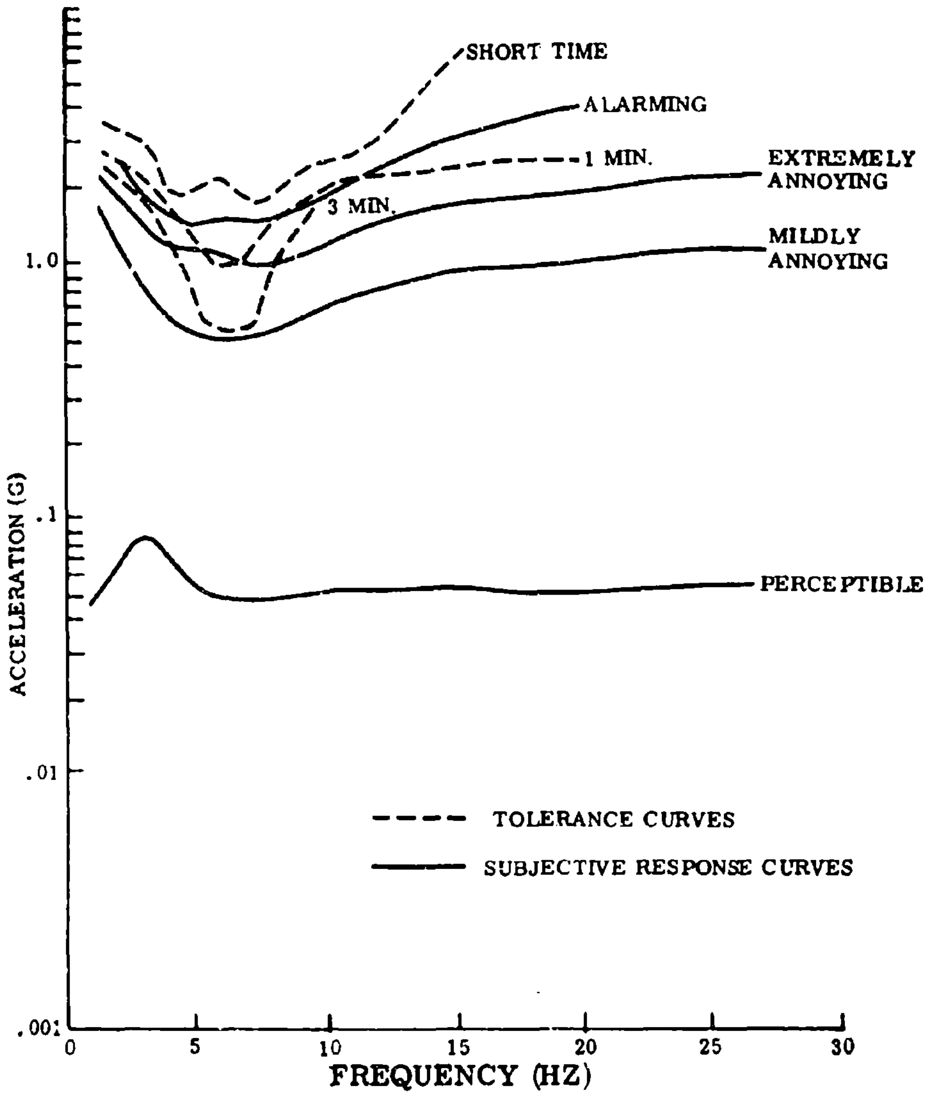
SUBJECTIVE HUMAN VIBRATION RESPONSE CURVES (CHANEY, 1964)

FIGURE 3-4



CHANEY'S (1964) SUBJECTIVE RESPONSE CURVES COMPARED WITH THE TOLEREANCE CURVES OF GOLDMAN (1948)

FIGURE 3-5



SUBJECTIVE RESPONSE CURVES (CHANEY, 1964) COMPARED TO SHORT-TIME, 1-MINUTE AND 3-MINUTE TOLERANCE CURVES OF MAGID, COERMANN, AND ZIEGENRUECKER (1960)

FIGURE 3-6

Inspection of Figure 3-5 reveals that Chaney's (1964) subjective response curves are associated with higher acceleration levels than the "tolerance" curves reported by Goldman (1948). Perhaps this result is attributable to the fact that Goldman's curves were synthesized from data collected in a wide variety of formats and from subjects tested in various postures and experimental settings. Moreover, the orientation of Goldman's research subjects was toward "tolerance" of vibration inputs as it affected physical comfort in subjects who were essentially passive recipients of the vibration inputs. Chaney's research method emphasized standardized treatment of test subjects, tight experimental controls, apparatus refinements and duty or work-oriented frames of reference on the part of his vibration subjects.

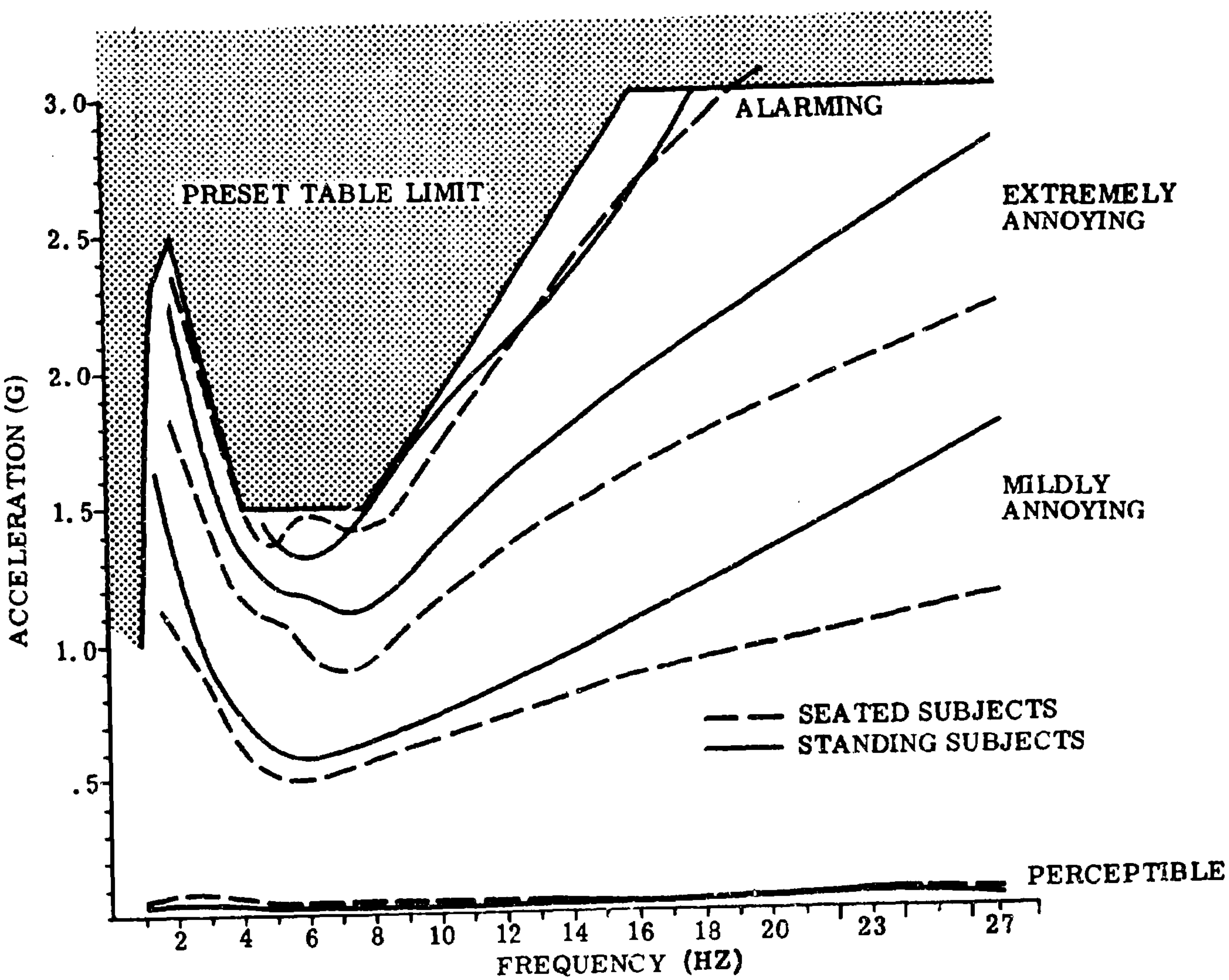
Figure 3-6 compares Chaney's subjective response curves to the short-time, three-minute and one-minute tolerance curves of Magid, Coermann and Ziegenruecker (1960). Some overlap of acceleration levels is apparent among the curves reported by Magid et al and Chaney, particularly in the 5-10 Hz frequency range. Above 10 Hz the curves manifest a rank ordering so that the more menacing a given verbal label, the higher the acceleration level associated with the label. Chaney's "perceptible" curve is associated with lower acceleration levels than any of the other curves because of the qualitative difference between the "perceptible" subjective response and the other subjective response and tolerance terms.

3.2.3 Reaction of Standing Subjects

Chaney (1965) extended his study with standing subjects restrained at the feet, rather than with seated subjects. The subjects made the same four subjective ratings concerning the same family of frequencies as before, and again had control of vibration amplitude.

Vibration was transmitted through solid blocks on which the subject stood. The blocks incorporated a restraint system involving special boots which laced to the subject's ankles, and was set to provide 30 pounds restraint at the feet. The blocks were located to allow the subject to assume a normal standing posture (heels slightly apart, toes turned slightly outward). Legs were held straight, with the knees neither flexed or locked.

Chaney reported subjective reaction curves (Figure 3-7) which closely paralleled in shape those for his seated subjects. At the intermediate severity levels (annoying and extremely annoying) the curves for standing subjects were higher than their counterparts for seated subjects. This means that greater acceleration levels were required for identifying the intermediate subjective reaction levels and implies that the standing human is a better shock absorber than the seated one. The amplitudes of vibration judged alarming by the standing subjects were nearly identical to amplitudes judged alarming by seated subjects; and, although tolerance to vibration of standing subjects was generally greater, the frequency band 4-8 Hz was once more found most critical to comfort.



SUBJECTIVE REACTION CURVES-SEATED AND STANDING SUBJECTS (CHANEY, 1964,1965)

FIGURE 3-7

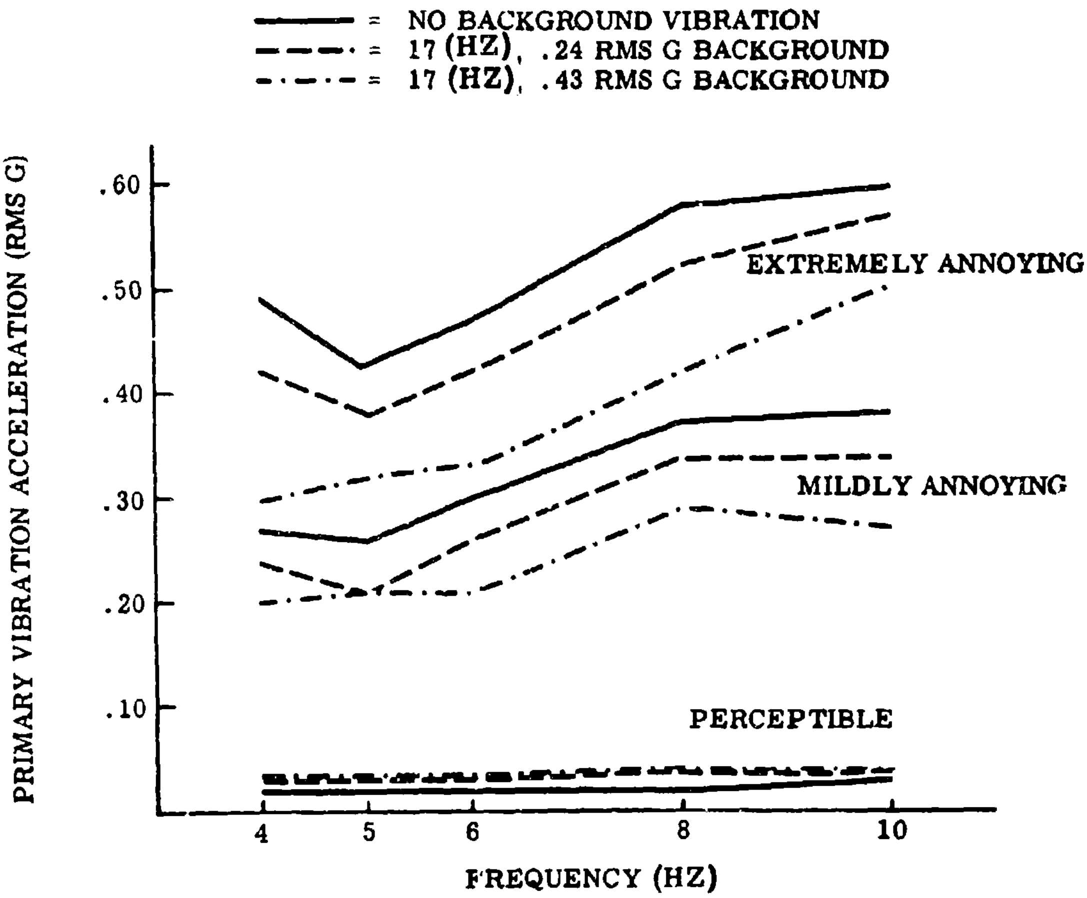
3.2.4 Reaction to Dual Frequency Vibration

The most recent study (Brumaghim, 1967) of the ONR series was designed to obtain data concerning reaction to dual frequency vibration. Subjects rated "Perceptible", "Mildly Annoying", and "Extremely Annoying" levels of sinusoidal vibration in the 4 to 10 Hz range under three vibration background conditions (Figure 3-8). The background conditions were (a) no vibration; (b) 17 Hz vibration at 0.38 peak g; and (c) 17 Hz vibration at 0.68 peak g. When frequencies were combined in this manner the subjects were instructed to rate only the variable frequency and not to attend to the background frequency.

The subjective reaction curves (Figure 3-9) obtained with no background vibration generally supported previous results. Lower levels of "Mildly Annoying" and "Extremely Annoying" thresholds were identified as the intensity of the background vibration was increased. The shapes of the subjective reaction curves were similar when ratings were made in the presence of the 0.38 g, 17 Hz vibration. However, when the 0.68 g, 17 Hz background was used, the "Mildly Annoying" thresholds dropped as the difference between the primary and background frequencies increased. The "Extremely Annoying" subjective reaction curve again resembled the shape obtained when no background vibration was present.

		Subjective Level	Primary Frequency (HZ)				
			4	5	6	8	10
Background Vibration (17 HZ)	.68g	Perceptible					
		Mildly Annoying					
		Extremely Annoying					
	.38g	Perceptible					
		Mildly Annoying					
		Extremely Annoying					
	0g	Perceptible					
		Mildly Annoying					
		Extremely Annoying					

THE EXPERIMENTAL CONDITIONS (BRUMAGHIM, 1967)
FIGURE 3-8



SUBJECTIVE REACTION CURVES AS FUNCTION OF FREQUENCY OF PRIMARY VIBRATION AND AMPLITUDE OF BACKGROUND VIBRATION (BRUMAGHIM, 1967)

FIGURE 3-9

4.0 EFFECTS OF VIBRATION ON SENSORY-MOTOR PROCESSES

4.1 Measuring Performance

These studies differ from the subjective reaction group in that they impose a greater workload on the vibrated subject. In addition to encountering vibration at the four severity levels across a 1-27 Hz band of frequencies, the subject has to react to visual or auditory signals, discriminate tones, relay verbal messages. adjust dials, read numerals, or adjust simulated displays of aircraft heading and pitch. His task loading may vary, the forces required to operate the controls may vary, and the color and brightness of illumination at the displays may vary. The presence of task loading, the mixing of vibration and visual/auditory inputs, and the dual nature of the subject's responses (sensory and motor) all appear to contribute to a general difficulty in integrating the results of these studies. Clearly, more work in the vibration plus sensory-motor response area is needed, including better methods in performance measurement. The five studies to be reviewed briefly will illustrate these points.

4.2 Sensory-Motor Processes Studies

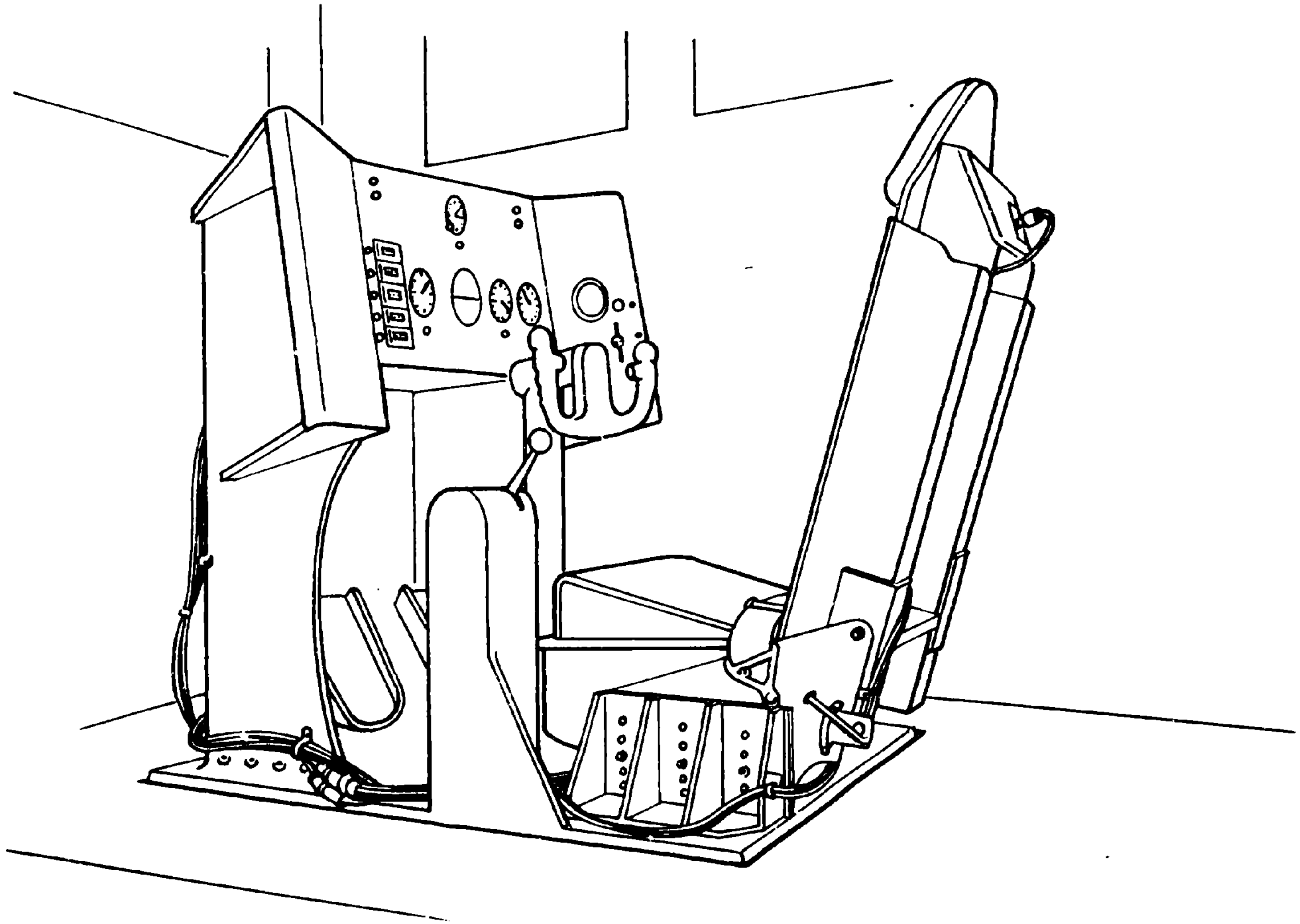
4.2.1 Effects on Speech and Hearing Intelligibility

Teare (1963) reported a study which measured binaural thresholds to four tones (500, 1000, 2000 and 4000 Hz) and recorded spoken messages from eight male subjects who performed these tasks under perceptible, mildly annoying, extremely annoying, and alarming levels of vibration severity. Sinusoidal frequencies ranged from 1 to 27 Hz, with a zero vibration control condition for establishing baseline tone thresholds and speech intelligibility.

Teare reported that threshold increased with vibration, but non-systematically. The changes which were noted were judged too small to have operational significance. Vibration likewise had little effect on speech intelligibility, except that subjects tended to speak in short bursts under the lower frequency vibration conditions (2-8 Hz), the range within which internal organ displacement is thought to be most marked (Magid et al, 1960; and Parks & Snyder, 1961). This study did not adequately test the impact of vibration on speech intelligibility. The material iterated by the vibrating test subjects consisted of well-known phrases which may have biased the responses of the panel of intelligibility judges.

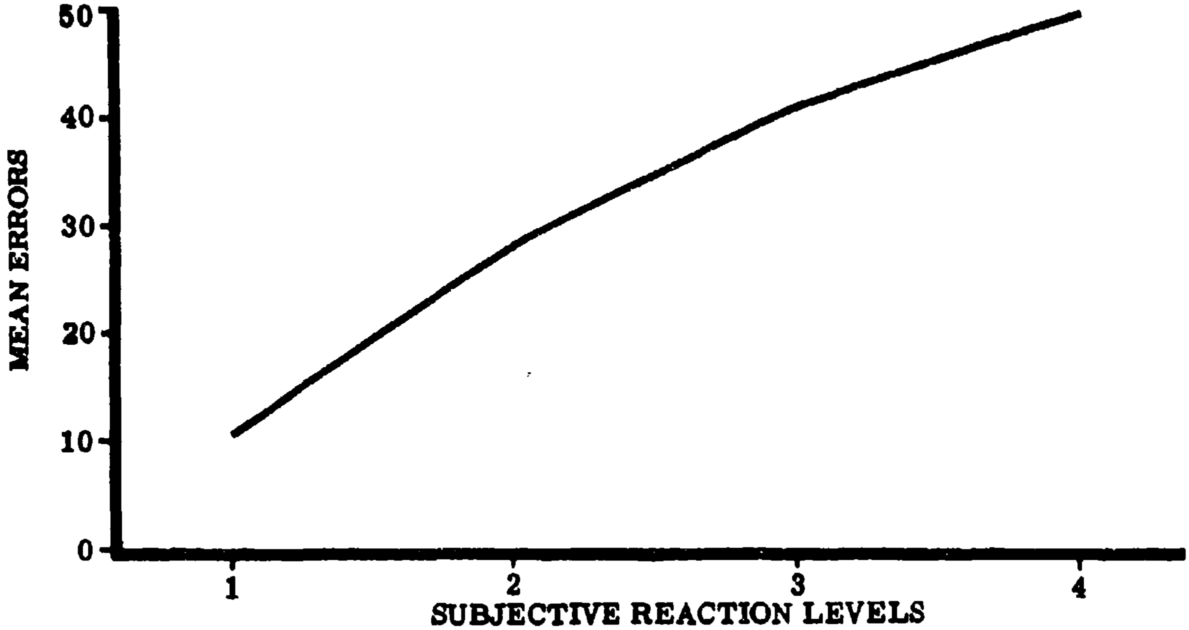
4.2.2 Effects on Visual Performance Under Normal Illumination

Teare and Parks (1963) next studied counter reading performance under a variety of vibration conditions (1-27 Hz, four subjective severity levels). The test configuration is presented in Figure 4-1. Eight subjects read five counters each displaying five digits varying from .05 in. to .20 in. At a viewing distance of 28 in. these displays subtended 6 to 24 minutes visual angle. Vibration severity and frequency affected readability (Figures 4-2, 4-2a and 4-3), but the decrement was restricted to digits subtending less than 12 minutes visual angle (Figure 4-2a) and to frequencies ranging between 10 and 23 Hz (Figure 4-3). Readability of even the smallest digits actually improved from 23 to 27 Hz, a result apparently attributable to the formation of distinct double images at higher frequencies coupled with the asynchrony which



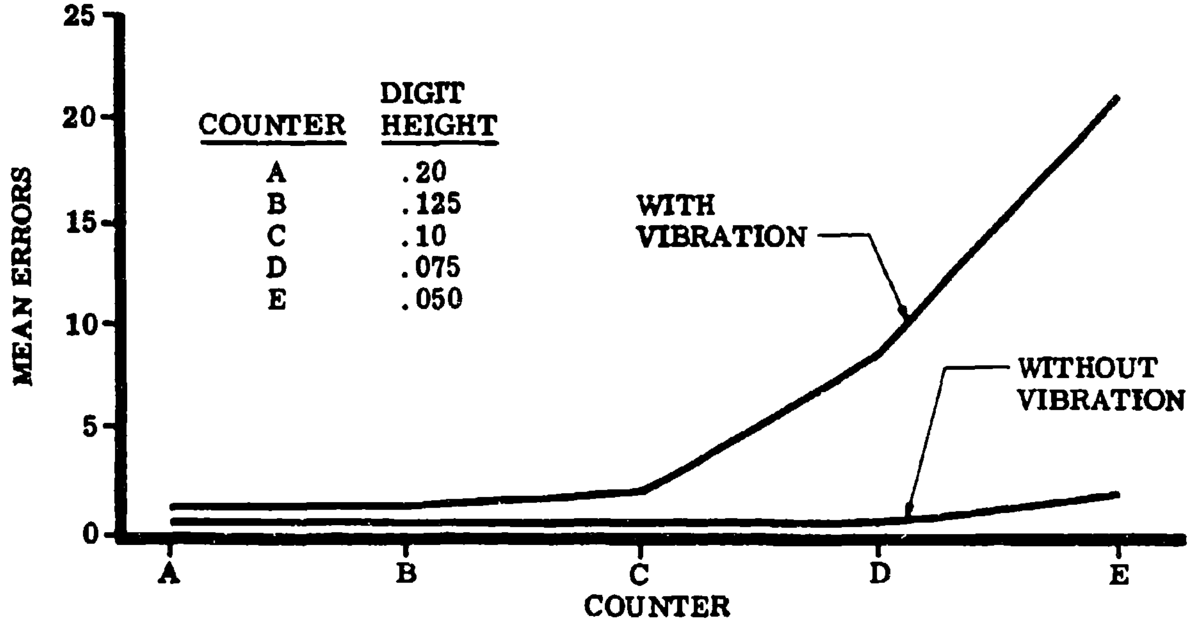
TEST STATION CONFIGURATION (TEARE & PARKS, 1963)

FIGURE 4-1



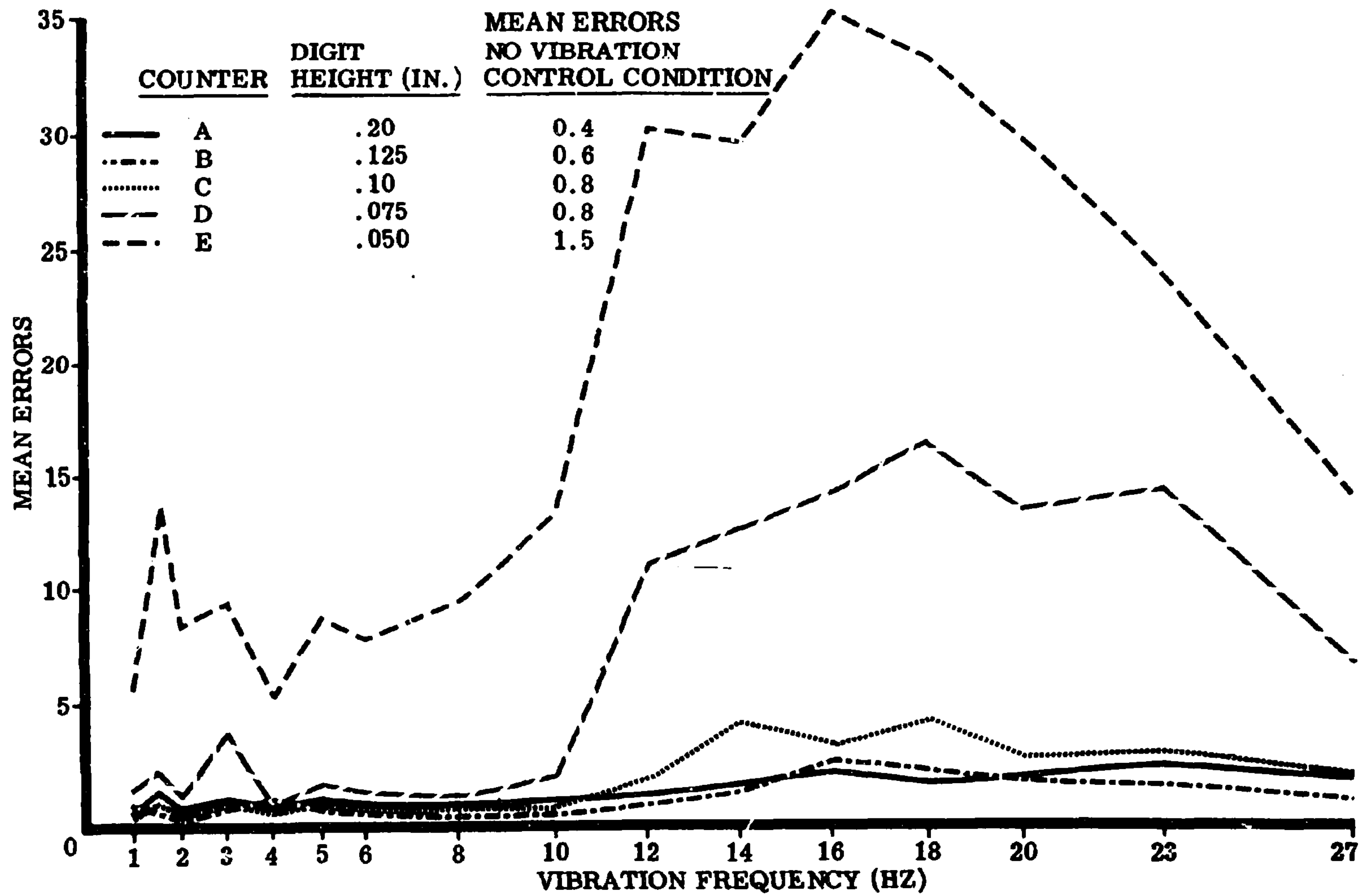
MEAN ERRORS (5 COUNTERS) BY LEVEL
(TEARE AND PARKS, 1963)

FIGURE 4-2



VIBRATION AND NO VIBRATION ERRORS FOR EACH COUNTER
(TEARE AND PARKS, 1963)

FIGURE 4-2A



MEAN ERROR (BY FREQUENCY) FOR EACH COUNTER
(TEARE AND PARKS, 1963)

FIGURE 4-3

developed between the subject and the display at the higher frequencies. Marked readability decrement, which began to be evident at around 10 Hz, was discussed in terms of critical flicker frequency of the human eye. It should be emphasized that, for the larger digits, legibility degradation was not marked. A review of the effects of vibration on man's visual capabilities in space is presented by Snyder (1965).

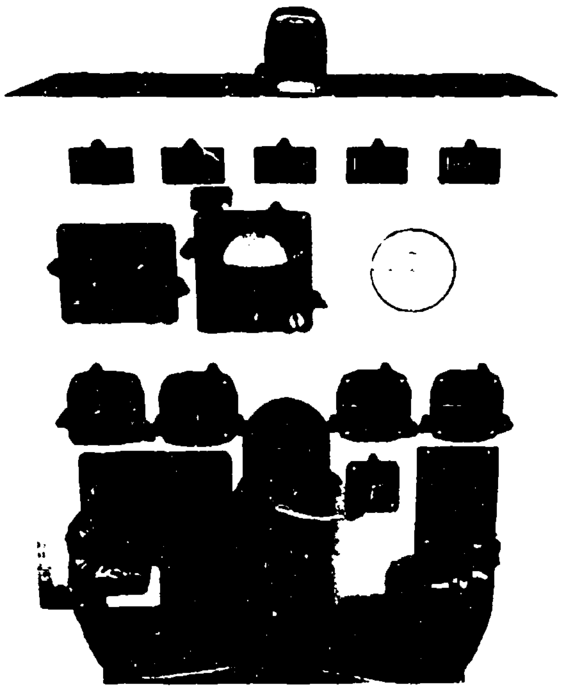
4.2.3 Effects on Visual Performance under Reduced Illumination

Morris (1966) investigated numeral reading performance of five subjects under four vibration conditions (1Hz, 6Hz, 16Hz, and random frequencies), two illumination colors (red and white), and three display luminances (1.00, 0.10, and 0.01 ft-L). This study, funded by The Boeing Company, assessed vertical and horizontal compensatory tracking performance under these conditions as well. The display panel is shown in Figure 4-4. Morris reported (Figure 4-5) degraded numeral reading performance at 16 Hz for both the 0.10 and 1.00 ft-L luminances; but at the lowest brightness level, 0.01 ft-L, the greatest decrement in numeral legibility occurred with 6 Hz vibration. In practical terms this finding implies that numeral reading performance suffers when reduced illumination is required and low-frequency vibration is encountered. A related finding for the lowest brightness level was that red lighting produced the fewest reading errors regardless of vibration condition. At the higher luminance levels red lighting was better for numeral reading in the three sinusoidal vibration conditions but not with random vibration. In general, degraded numeral reading at 6 and 16 Hz (Figure 4-6) agrees with Teare's results (1963), so that one can be fairly confident in predicting numeral reading errors when the operational environment includes vertical vibration in the range of 6-23 Hz.

Summarizing the Teare and Morris results, it appears that low frequency vibration has little degrading effect on tone discrimination or speech intelligibility for well-known materials, but does have decremental effects on numeral reading ability for small digits. The degradation appears to increase as luminance level declines with white lighting, but red lighting seems to prevent reading decrement to some extent.

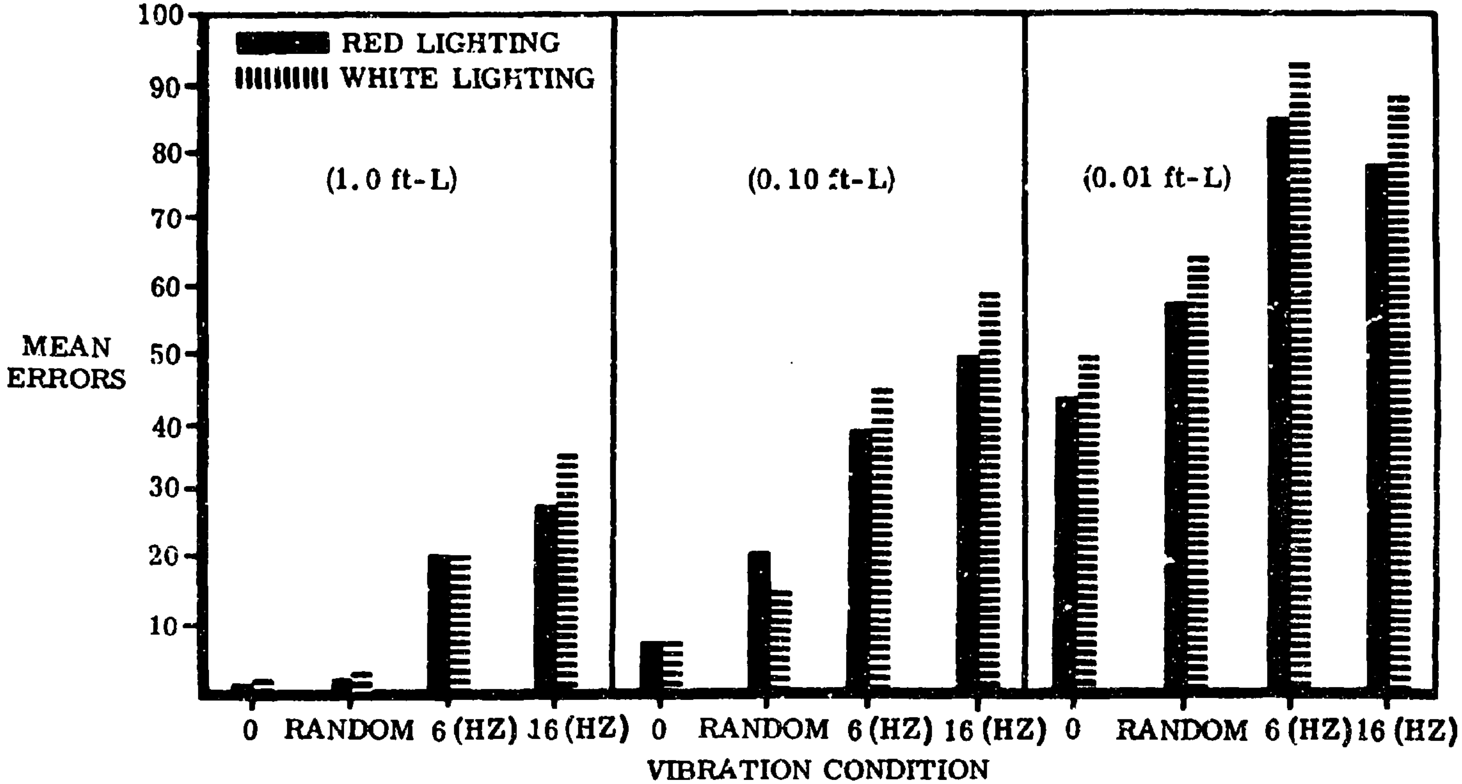
4.2.4 Effects on Horizontal and Vertical Compensatory Tracking

The apparent superiority of low intensity red lighting is confined to numeral reading, however, since Morris also reports that vertical and horizontal compensatory tracking were better under low level white than red illumination (Figure 4-7 and 4-8). The higher brightness levels failed to discriminate between red and white lighting in effectiveness when the task called for vertical tracking; however, horizontal tracking was better across all experimental conditions when the illumination color was white. A note of caution is appropriate here in that the tracking display, a CRT, produced higher luminances under white than under red (filtered) illumination. Thus, the superiority of white lighting for horizontal tracking may have been an artifact of brightness differences. Interestingly, horizontal tracking was not significantly degraded by any of the vibration conditions, whereas vertical tracking was affected. The greatest decrement to performance in vertical tracking was associated with 6 Hz sinusoidal vibration. It should be noted again that vibration was in the vertical axis.



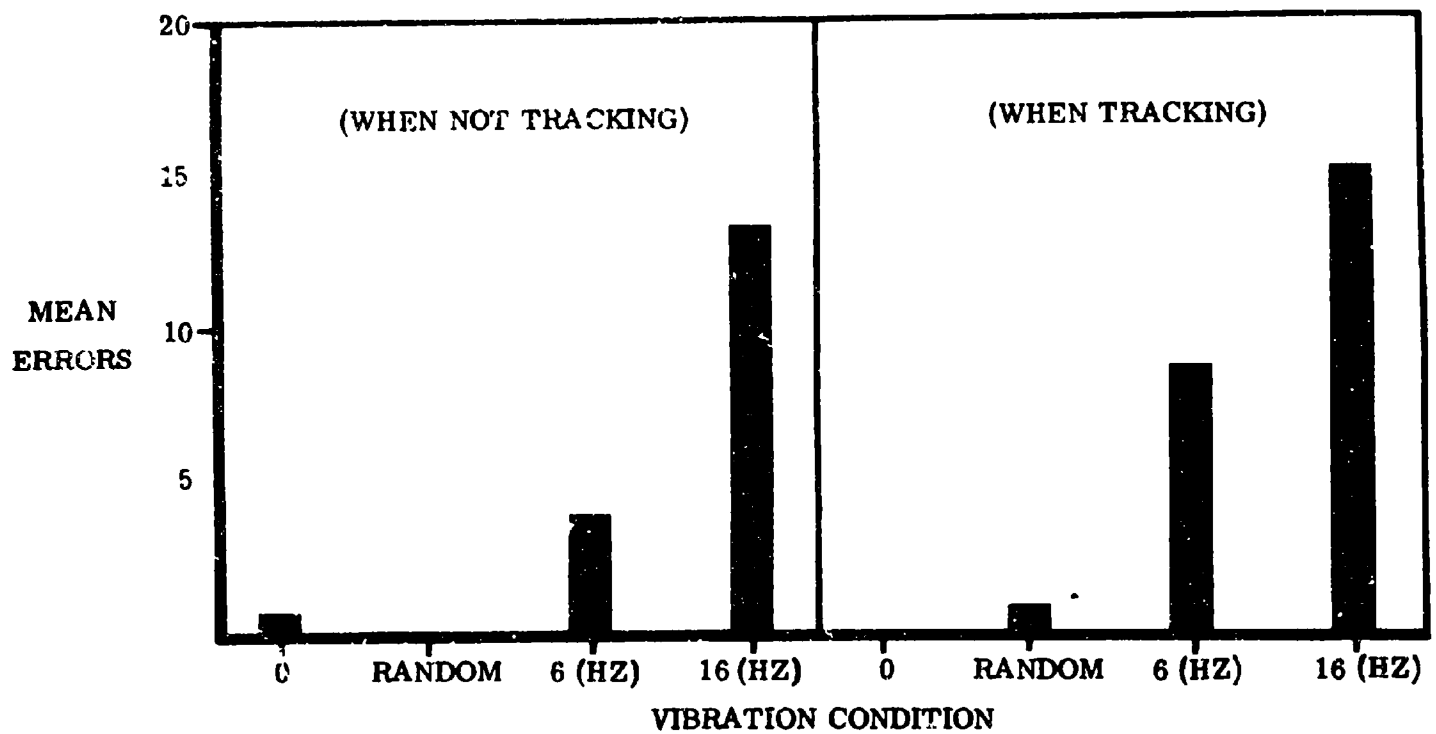
INSTRUMENT DISPLAY PANEL (MORRIS, 1966)

Figure 4-4



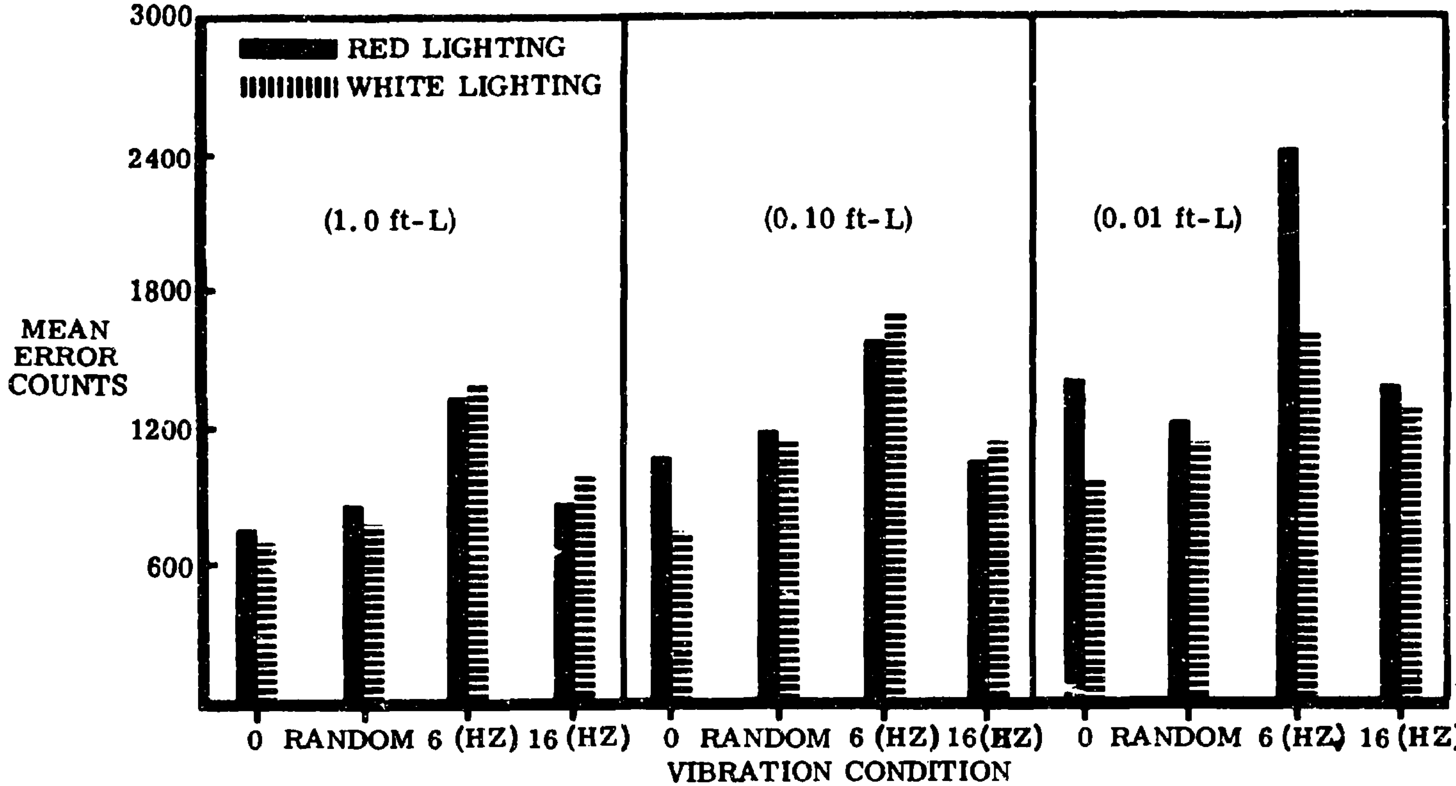
MEAN COUNTER ERROR SCORES WHEN NOT TRACKING (MORRIS, 1966)

FIGURE 4-5



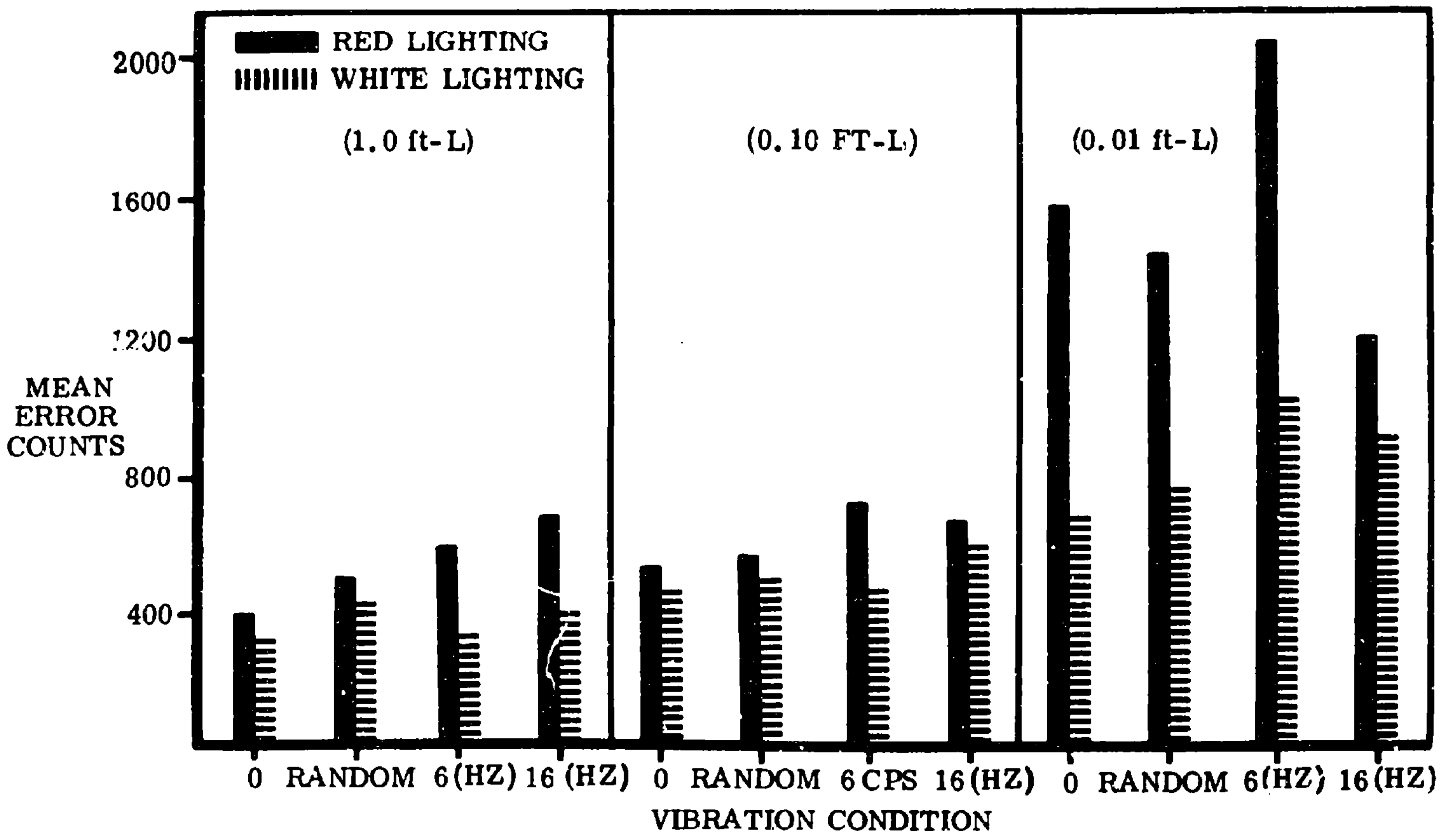
MEAN COUNTER READING ERRORS UNDER AMBIENT ROOM LIGHTING (MORRIS, 1966)

FIGURE 4-6



MEAN CRT TRACKING ERROR SCORES WHEN NOT READING COUNTERS (MORRIS, 1966)

FIGURE 4-7



MEAN HEADING TRACKING ERROR SCORES (MORRIS, 1966)

FIGURE 4-8

The relationship between vibration severity and compensatory tracking was explored by Chaney and Parks (1964a), whose seven subjects performed wheel, column, and foot tracking tasks under vertical whole-body vibration (1-27 Hz, four subjective severity levels). The display/control panel used is shown in Figure 4-9. Of special interest to the designer is their finding that tracking proficiency decreases systematically as vibration severity increases. Regardless of frequency, tracking deteriorated as the severity of vibration increased from zero (baseline) to perceptible to mildly annoying, then to extremely annoying, and finally, to alarming. Greatest breakdown in tracking occurred when vibration frequency was in the range 10-20 Hz. An interesting sidelight on the foot tracking task (i.e., rudder pedals) was that performance improved when control force requirements increased from 50 to 100 to 150 lbs.

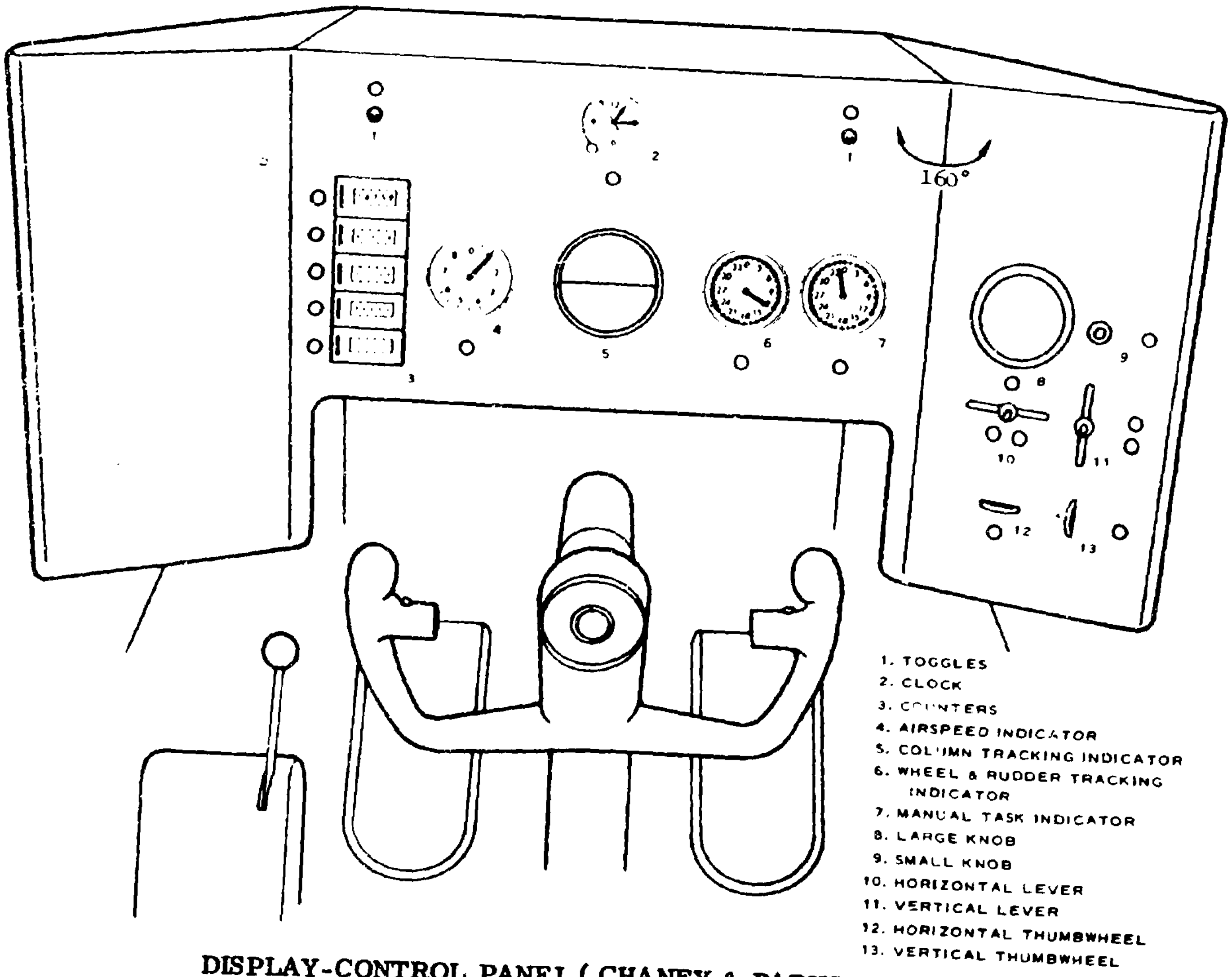
4.2.5 Interaction of Vibration and Workload

The complex roles of workload, vertical and lateral direction of control movement, and control force requirements in determining performance under vibration conditions were investigated by the same authors (Chaney and Parks 1964b). Seven subjects were required to adjust a three inch dial indicator to prescribed settings by means of a large and small knob, vertical and horizontal levers, or vertical and horizontal thumbwheels (Figure 4-9). Vibration frequency and severity varied, as did required control forces and subject workload. The main data were speed and accuracy of achieving the dial settings.

Whereas accuracy of dial setting was not affected by type of control, time required to achieve a dial setting was affected by control type such that controls which required a vertical movement consumed the most time. Also, as control force increased from 2/3 lb. to 2 lb., time required for control adjustments increased. The addition of vibration to the environment had the effect of increasing both adjustment time and adjustment errors in this portion of the experiment, referred to as the moderate workload condition. Vertical tracking and vertical control settings were most affected.

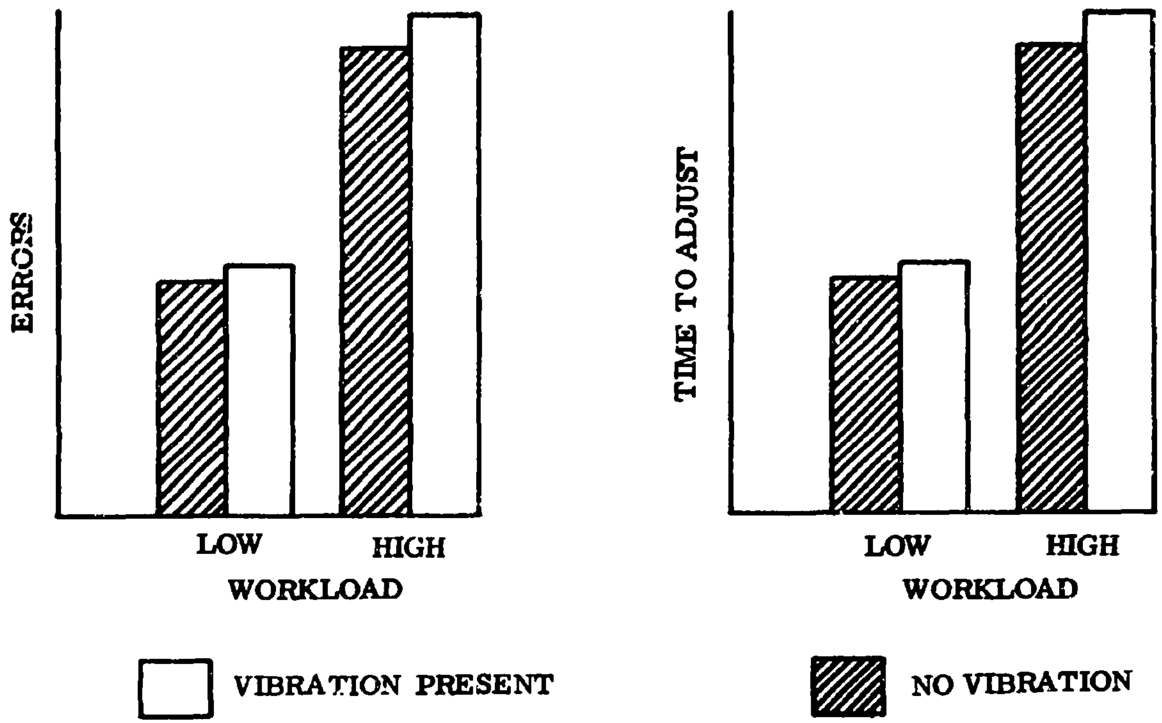
The high workload condition was achieved by maintaining the dial setting task in total and reinstating the vertical and horizontal tracking tasks. Additionally, the subjects were required to adjust simulated airspeed, read and report counter numerals, activate toggle switches, and report clock settings. Cueing lights directed the subject to his next response. The results of the inflated workload (Figure 4-10) clearly showed that the high workload caused error increases in dial setting and that vibration per se tended to be insignificant as an additional source of error. The performance decrement, of the order of a doubling or tripling of errors, was with reference to the same responses as those involved in the moderate workload portion of the experiment (knob, lever, and thumbwheel manipulation with force requirement fixed at 1 1/3 lb.). Other tasks in the high workload experiment were simply designed to impose a high workload and were not studied systematically.

With a low workload the role of vibration was again fairly clear: it seemed to increase dial setting errors. With a high subject task loading (actually, overloading) vibration failed to worsen performance already degraded by the work schedule.



DISPLAY-CONTROL PANEL (CHANEY & PARKS, 1964a)

FIGURE 4-9



WORKLOAD VERSUS VIBRATION (CHANEY & PARKS, 1964b)

FIGURE 4-10

4.2.6 Effects on Crew Activities

Perhaps the most demanding study of the effects of vibration on crew activities under high workload conditions in this program was that undertaken by Parks (1965) in a Boeing-funded project. Six subjects were exposed to simulated low level turbulence in two extended tests (5 hours, 10 minutes duration, and 4 hours duration). Vibration intensities varied from .023 to .175 RMSg's. Subjects performed terrain-following and heading maintenance tasks and, during intervals of inflated workload, reacted to a warning light by turning off a toggle switch. Digital counters were also read out on signal during the periods of high workload. The same tasks were performed over the same time periods without vibration to isolate performance decrements that resulted from elapsed time alone. Performance was sampled at regular intervals for both the vibration and no vibration conditions.

Parks found that the immediate effects of vibration were indicated only on the terrain following task in which tracking under vibration was 39 percent poorer than tracking without vibration. The ability to maintain heading worsened as time elapsed under both the vibration and no vibration conditions. Vibration in itself had no significant effects on digit legibility, toggle switch response, or heading maintenance.

5.0 PHYSICAL EFFECTS OF VIBRATION

5.1 Reported Sensations

The subjective reaction studies, in which the subjects identified the four vibration severity levels across a frequency band of 1-27 Hz, have provided a format for the study of the many transient sensations which accompany whole-body vibration. Parks and Snyder (1961) and Chaney (1964) have developed extensive catalogs of the bodily sensations reported by seated subjects across the frequencies emphasized in the Boeing vibration studies. Chaney (1965) has provided similar information for the standing subject undergoing whole-body vibration. In general, the reports solicited from the subjects have emphasized sensations of a disturbing or even painful character, involving itching, flapping or shaking of skin or appendages, mild pain, pressure, perceived tightness, or functional hindrances such as swallowing difficulty, and blurring of vision. Reports of distinctly painful sensations and sensations of dizziness (or nausea) have also been included when reported.

5.2 Relationship between Frequency and Sensation

5.2.1 Head and Face Region

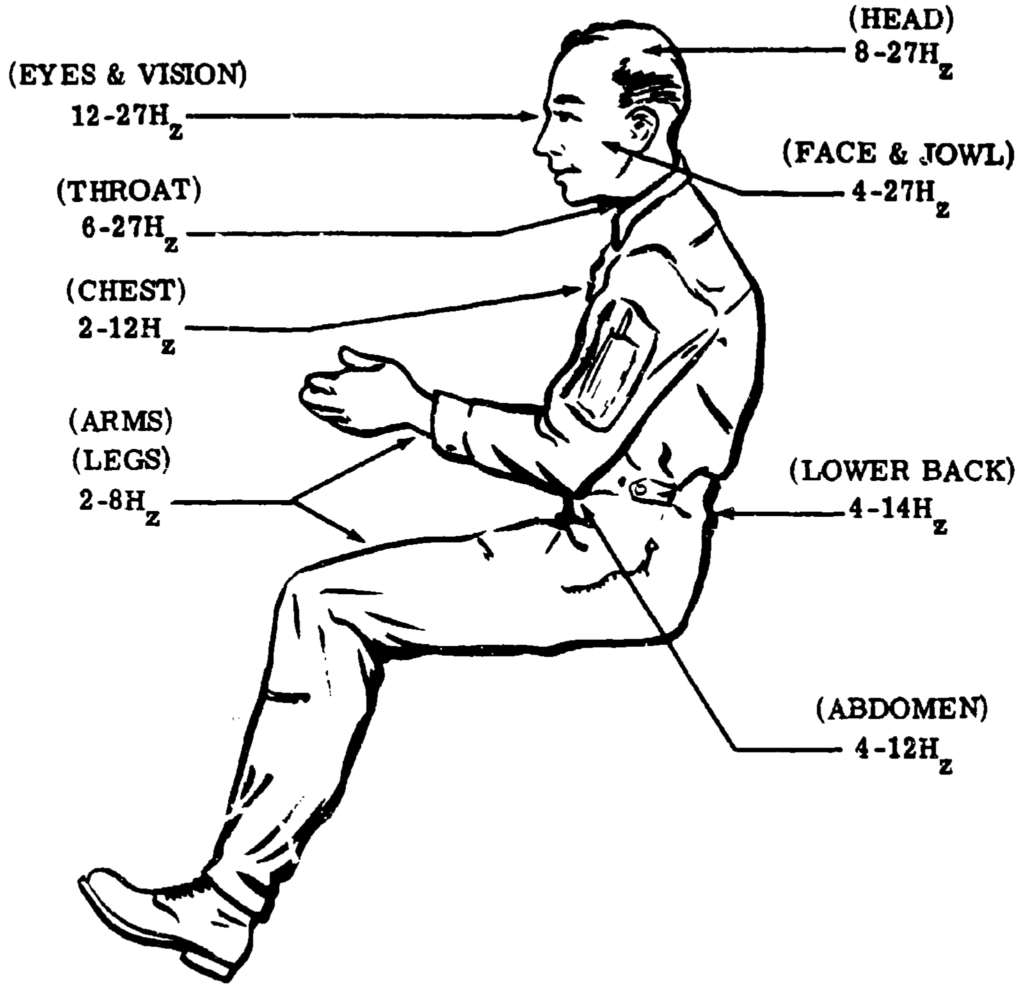
Parks and Snyder (1961) reported a high concentration of disturbing sensations or pain in the head and face in a frequency range of 8 to 27 Hz. Included in the experiences of their subjects was blurring of vision, which was reported as well by Chaney for both seated and standing subjects (Chaney reports the onset of blurring at about 12 Hz). In the same frequency range are included such sensations as ear itch, teeth chatter, skin displacement, lump in the throat or swallowing difficulty. These sensations were reported by both seated and standing subjects. In addition, the standing subjects reported bowel and bladder pressures or pains at these higher frequencies.

5.2.2 Abdomen, Chest, and Lower Back

It is the lower frequency range (1-14Hz) which is associated with the more severe family of responses to vibration, for it is in this region that abdominal, chest, and lower back pains become fairly common. The seated subjects reported back pains in the 4-14Hz region, abdominal pains at 4-12Hz, and chest pains at 2-12Hz. The standing subjects corroborated these figures, in general, with no distinct differences as a function of standing position noted. A summary of the effects of vibration on the different body areas is given for seated subjects (Figure 5-1) and standing subjects (Figure 5-2).

5.2.3 Vibration and Discomfort Overview

Thus low frequency vibration (1-14Hz) has a pronounced aversive impact on the trunk and internal organs, whereas higher frequency vibration (15-27Hz) is disturbing to the head region, its parts, and their functions. The head region is not as subject to the occurrence of pain as is the abdominal region, but its family of sensations may be equally disconcerting to the human operator.



CONCENTRATIONS OF DISTURBING SENSATIONS
AND RANGES OF FREQUENCIES

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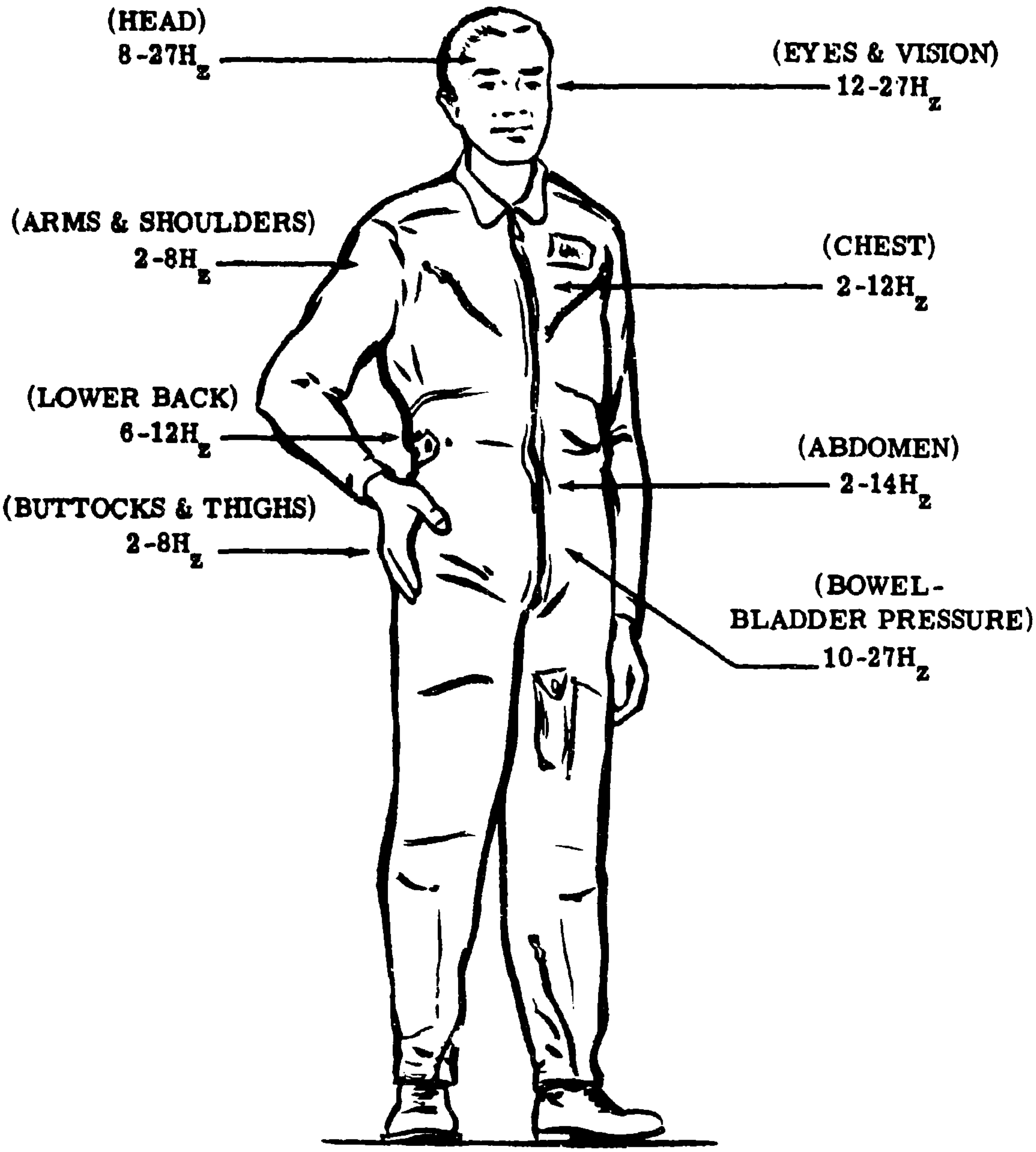
Figure 5-1



CONCENTRATIONS OF DISTURBING SENSATIONS
AND RANGES OF FREQUENCIES

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Figure 5-2

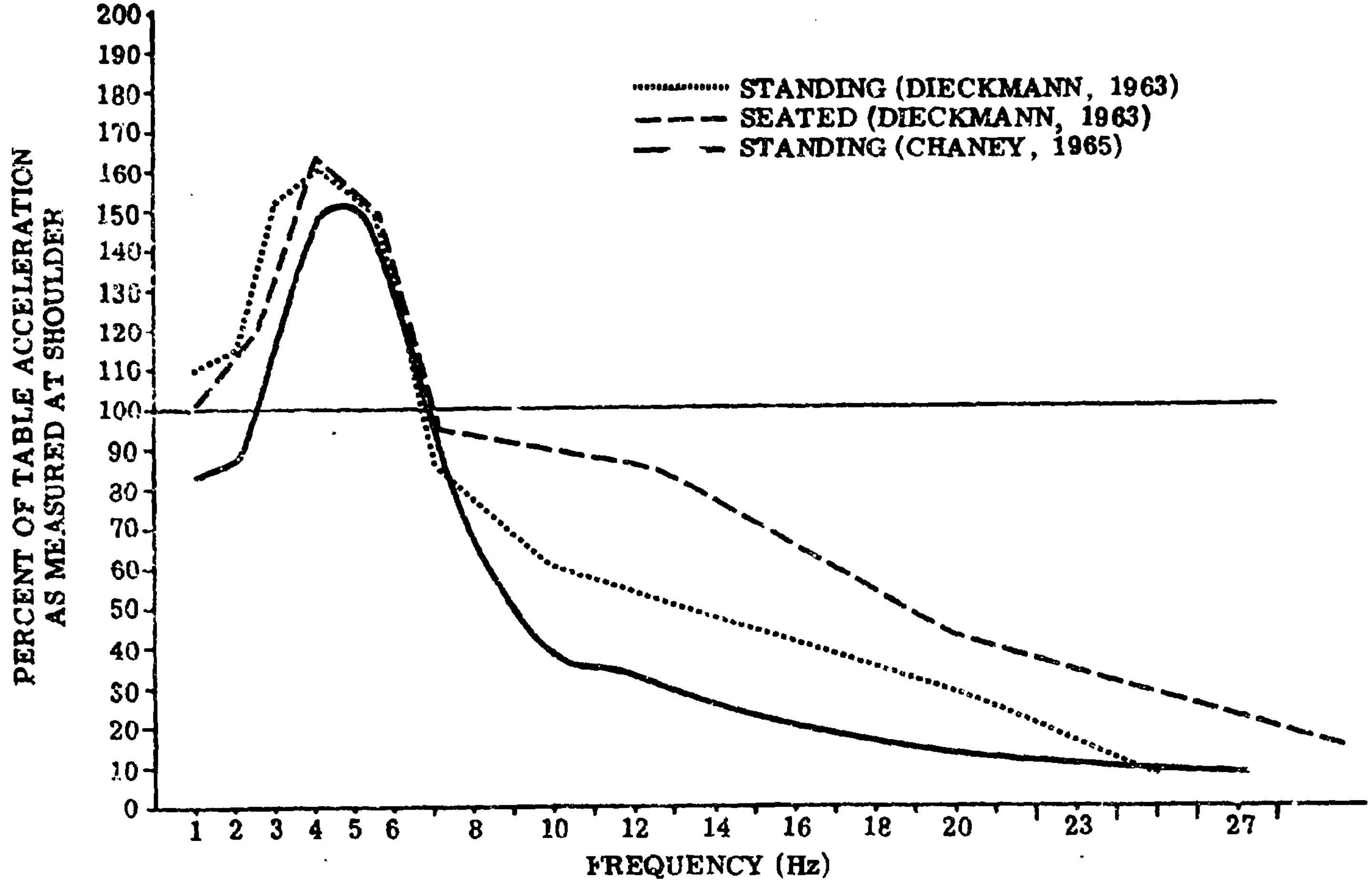
Considering the body as a whole, Parks and Snyder (1961) report a greater incidence of disturbing sensations in the 1-10 Hz frequency range than in the 12-27 Hz region. Chaney's data on standing subjects suggest the same results: that the relative impact of lower frequency vibration is greater than that for higher frequency vibrations.

Although reports of dizziness, nausea, and motion sickness were rare in these studies, it is interesting to note that when nausea or motion sickness was reported, it tended to occur at very low frequencies (1-3 Hz). Dizziness, on the other hand, was reported in the intermediate frequency range (5-27 Hz) (Chaney, 1965).

Also noteworthy is that the extremities and/or masses such as shoulders, arms and legs, and buttocks (standing subjects) seem to respond most vigorously at the lower frequency vibration (2-8 Hz). And, although Chaney's standing subjects reported bowel and bladder pressure and pain only at intermediate frequencies (10-27 Hz), it seems more likely that these sensations were present at the lower frequencies, but were masked out by other abdominal, back, and chest sensations.

Figure 5-3 presents acceleration at the shoulder expressed as a percentage of the acceleration measured at the vibration table.[1] It is clear that low frequency vibrations lead to higher shoulder percentages and actually lead to an augmenting of the acceleration force acting on the shake table. Beyond frequencies of 8 Hz there is a damping effect evident at the shoulder, in that shoulder acceleration levels are lower than those measured at the table. Only at around 1 Hz and 8 Hz do outputs at the shoulder match table inputs. Such data support the various models of man in motion which emphasize his mass and springing-damping capabilities (e.g., Goldman and von Gierke, 1961).

[1] Figure 5-3 includes data from studies of D. Dieckmann as reported in Morgan, Cook, Chapanis and Lund (Eds.), Human Engineering Guide to Equipment Design, New York, McGraw-Hill, 1963



SHOULDER ACCELERATION EXPRESSED AS A PERCENTAGE OF TABLE ACCELERATION

Figure 5-3

6.0 RETROSPECT AND PROSPECT

As in much research, one of the major results of the vibration research supported and stimulated by the Office of Naval Research is a depth of understanding and personal insight accruing to the researchers which is impractical to communicate through the medium of technical reports. The following comments, offered in retrospect, are an attempt to communicate some of this insight and to suggest directions for future exploration.

Man is almost constantly experiencing vibration of varying characteristics and severity. He encounters it in some degree whenever he is transported - be it by automobile, bus, train, boat, airplane, rocket or on foot. Even in the relative quiet of his home there are numerous sources of vibration. While man has become conditioned to the point that he is either unaware of this vibration or is unemotional about it, we cannot be certain that it does not affect his general physical and mental condition with implications for his efficiency and capacity. Vibration in space vehicles and vibration in air, land, and water vehicles is a subject of grave concern to the designers of manned systems. Researchers have identified with reasonable accuracy, the levels of vibration beyond which man cannot go with impunity. The question of how well he can perform various tasks under vibration levels short of this limit is much more complex and not nearly so well defined. Man voluntarily subjects himself to vibration in numerous sports and recreational activities, such as horseback riding, speed boating, auto racing, skiing, etc. He also supports a large business in vibration couches, chairs, cushions and belts. Whether physiological or psychological, there is apparently some benefit to the users of these devices. This beneficial aspect of vibration has not received the same attention as have the detrimental aspects, yet it is quite possible that vibration may serve a valuable function in adapting man to his environment in tomorrow's advanced systems.

That the rather large store of data accumulated on the subject of vibration effects provides such a small bank of useful information does not fault the researchers so much as it indicates the extreme complexity of the vibration problem. A few general statements concerning vibration effects can be made with some confidence despite the need for persisting research efforts in vibration environments:

a. Man will voluntarily accept relatively high levels of vibration while doing a job.

b. Man is less tolerant of vertical vibration in the range of 4 to 10 Hz. than of frequencies outside that range.

c. There is wide variation in individual acceptance of vibration.

d. Vibration acceptance is affected by other environmental stimuli, as well as by motivation and mental attitude.

e. Some vibration conditions are apparently pleasant (at least for short periods of time).

f. The present state-of-the-art does not allow sinusoidal laboratory vibration test results to be extrapolated to complex real world vibration environments with a high degree of confidence.

In order that continuing and future research in this area be meaningful and useful, it is desirable to strive for greater standardization of test conditions, methods, stimuli and measurements. Some of the more critical items are:

a. All test conditions, both constants and variables, should be accurately and precisely recorded.

b. The ambient environment of the test subjects should be controlled (according to a standard set of conditions if feasible) and precisely recorded.

c. The accurate wave form of the vibration must be documented along with frequency and intensity.

d. The vibration input to the subject must be measured at the point of application to the subject.

e. If vibration in only one plane is being considered, motion in planes normal to the primary should be minimized, measured and recorded.

Some of the problems which need solution or at least definition if useful and generalized data are to result include the following:

a. Devise some means of defining real world vibration spectra in terms meaningful from the standpoint of human response - physical, physiological, psychological and performance, and make possible the replication of vibration conditions.

b. Develop better means of describing a test vibration environment in precise terms and dimensions which contribute to the human reaction to that environment. This requirement applies to single frequency, one axis motion as well as random multi-axis motion.

Until a means of assuring comparability of vibration conditions from a human response standpoint has been established, the only reliable way to assure that critical functions can be accomplished by human operators in complex vibration environments is to conduct tests in realistic environments, which include closely simulated operational vibrations. Such tests should include multi-axis motion with acceleration time histories as closely representative of the anticipated real environment as possible.

The question of possible beneficial effects of whole body vibration is deserving of more attention. Some areas for examination include the possibility of reduction of physical and mental fatigue, enhanced alertness, stimulating circulation, and improving tone of vital organs. Such effects might be be especially beneficial to persons unable to participate in "jogging" or exercise. The possibility of avoiding calcium excretion during long periods of weightlessness, by substituting vibration acceleration for the missing acceleration of gravity, has obvious implications for manned space programs.

Research now under way or programmed for near future investigations at The Boeing Company, Wichita Division, is directed toward pressing questions of immediate interest. Current research emphasizes development of passenger ride quality design criteria for air transport vehicles. The ride quality criteria will be used as one basis for the design of stability augmentation systems as required to ensure a comfortable commercial airplane ride. Studies have included vertical, lateral, combined axes and combined random vibration inputs in the 0 to 7 Hz range. Ride comparison tests will also be conducted to help evaluate the passenger ride quality benefits of several stability augmentation systems under study.

Future programs are planned to further refine and extend the development of ride quality criteria to flight crews. It is also planned to continue basic and applied research to define human performance capability in a vibration environment.

A number of follow-on studies are indicated for which research strategies and plans are being developed.

a. Continuation of passenger ride quality criteria development.

b. Crew ride quality criteria development.

c. Flight test validation of ride quality criteria developed in laboratory testing and computer analysis.

d. Development of flight instrument design criteria for use under all operational lighting and vibration conditions.

e. Instrument lighting requirements as a function of vibration and external illumination of visual targets.

f. Relative effectiveness of different types of control sticks and locations in a combined vertical-lateral random vibration environment.

g. Relationship of short to long duration vibration effects on ride quality criteria and on human performance.

A problem area that is less well defined, but is also recognized as one requiring research, is that of the effects of multiple stress, workload, and fatigue on crew performance ("multiple stress" would include vibration).

In addition, when resources are available to continue more fundamental research, the following areas should receive further attention:

a. Effects of lateral vibration on performance and subjective reactions.

b. Definition of random vibration to permit better correlation of quantitative vibration characteristics with test results.

c. Physiological effects of vibration as an aid to understanding total human response to a vibration environment.

d. Prediction of reactions to a multi-frequency vibration environment from knowledge of reactions to each component frequency alone.

e. Continued emphasis on definition of both input signals to the vibration system and the actual vibration environment experienced by the subject.

Finally, an extensive, systematic, and well-integrated program is urgently needed to develop a battery of well-defined, validated human tasks and measurement standards. Such a battery of performance measures and associated criteria would have application in any man-machine study area and with reference to any unusual environment, of which vibration is but one example. This would be an expensive and complicated undertaking, but the returns from developing a standard set of human task and performance criteria would be considerable in the areas of prediction, evaluation, and assessment of reliability of man-machine systems.

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B. Dissemination of Technical Information

Human vibration research has been a major activity of the Human Factors Staff at Boeing Wichita since 1957. This research, supported primarily by the Office of Naval Research, has led to 15 documents relating to studies conducted at the Wichita facility (Appendix A). In addition, four articles on vibration research have appeared in technical publications and staff members have read seven papers at technical or professional meetings. Two sound and color films depicting aspects of the research were produced and have been widely circulated.

In accordance with an ONR requirement, each of the subject research reports was distributed to 22 specified organizations or persons. However, the distribution list typically named over 250 recipients. The eleven company-funded vibration studies conducted in 1968 and 1969 for the purpose of establishing ride quality criteria for airline passengers can be pointed to as an obvious outgrowth of the ONR vibration research program.

However, it is more difficult to assess the larger contribution this program has made to the general technological community. Perhaps some indication of potential impact of the research can be gleaned from the material to follow in Appendix B. Two lists of names and/or organizations appear in the next few pages. The first list is comprised of organizations which requested and received copies of the vibration research reports. The second list contains the names and organizations of persons who have visited the Boeing Wichita vibration facility. Both lists are characterized by the diversity of interest groups they represent.

I. Organizations requesting vibration research data

a. Military and Government

United States Navy
- Bureau of Medicine and Surgery
- BUWEPS
- David Taylor Model Basin
- Naval Aerospace Medical Center
- Naval Air Development Center
- Naval Air Engineering Center
- Naval Air Systems Command
- Naval Medical Research Institute
- Naval Missile Center
- Naval Personnel Research Activity
- Naval Research Laboratory
- Naval Training Device Center

United States Army
- Armor Human Research Unit
- Aviation Human Research Unit
- Human Engineering Laboratories
- Land Locomotion Laboratories
- Transportation Research Command

United States Air Force

- Air Force Systems Command - Ballistic Systems Division
- Crew and AGE Subsystems
- Directorate of Aerospace Safety
- Strategic Air Command Headquarters
- Wright Air Development Division - ARDC

United States Government

- Defense Documentation Center
- FAA-Civil Aeromedical Research Institute
- FAA-Medical Library Branch
- National Bureau of Standards
- NASA-AMES Research Center
- NASA-Houston
- NASA-Langley Research Center
- Public Health Service- Occupational Health Research and Training Facility
- Scripps Institute of Oceanography

b. Aerospace Industry

- Bell Helicopter Corporation
- Douglas Aircraft - Saturn Division
- Grumman Aircraft Company
- Kaman Aircraft Corporation
- Martin Company
- Martin-Marietta Corporation
- McDonnell Aircraft Corporation
- North American Aviation
- Northrop Norair
- Northwest Airlines
- Republic Aviation

c. Associated and/or General Industry

- Bellcomm, Incorporated
- Bell Telephone Laboratories
- Bendix - Eclipse Pioneer Division
- Chrysler Corporation
- Dowty-Rotol Incorporated
- General Electric - Systems Integration
- General Motors Corporation Research Laboratories
- Goodyear Aerospace - Life Sciences Research
- International Business Machines
- Lear-Siegler Instrument Division
- Link Division - General Precision
- Litton Systems Incorporated
- Minneapolis-Honeywell Aero Division
- Niagara Corporation
- Outboard Marine Corporation
- The RAND Corporation

d. Academic/Training Institutions

Harvard University School of Public Health
Institute of Medical Sciences, Presbyterian Medical Center
Johns Hopkins University
Iowa State University
Massachusetts Institute of Technology
Michigan State University
New Mexico State University
New York University
Ohio State University
Texas A&M University
Tufts University
University of Illinois
University of Maine
University of Miami
University of Michigan
University of Virginia
University of Waterloo, Canada
Wayne State University

e. Consulting and research firms, foundations and publishers

Allied Research Associates
American Institute for Research
Bio-Sciences Information Exchange, the Smithsonian Institution
Bolt, Beranek and Newman Incorporated
Dunlap and Associates
Eye Research Institute
Flight Safety Foundation
Franklin Institute
Frost Engineering Development Corporation
The Lovelace Foundation
Machine Design Magazine
Rowland and Company
Serendipity Associates
Space Technology Laboratories
Technical Consultants, Incorporated
Trend Publishing Company
Worthington, Skilling, Helle and Jackson

f. International contacts

Akademia Medyczna, Warsaw, Poland
Arsenal de la Marine, Toulon, France
Charles University, Prague, Czechoslovakia
Department of National Defence, Canadian Joint Staff, Washington, D.C.
Defence Research Medical Laboratories, Toronto, Ontario, Canada
E.M.I. Electronics, Limited, Middlesex, England
Institute of Aviation Medicine, Feldbruck, Germany
Instituto Technologico de Aeronautica, San Paulo, Brazil
Laboratoires De Physiologie, Appliquee Au Travail Humain, Paris, France

Laboratoires Medico-Physilogique, Centre D'Essais, Paris, France
Laboratorio De Acustica E Sonica, San Paulo, Brazil
Max Planck Institut, Rheinlanddamm, Germany
National Physical Laboratory, Teddington, Middlesex, England
Royal Navy Bureau of Medicine & Surgery
Royal Navy - Scientific Intelligence
Royal Air Force Institute of Aviation Medicine, Farnborough, Hants, England
University College of South Wales & Monmouthshire, Cardiff, Wales
University College of Swansea, Singleton Park, Swansea, Wales
University of Queensland, Brisbane, Australia
Vickers-Armstrong Aircraft, Limited, Weybridge, Surrey, England

The human vibration facility, completed in 1959 and utilized since then for the many varied test programs, has attracted numerous visitors. A partial list of some of the visitors and their affiliation at the time of their visit is provided.

II. Visitors and Organizations

a. Military/Government

United States Navy
- Dr. Richard Trumbull - ONR - Washington, D.C.
- Dr. Gilbert Tolhurst - ONR - Washington, D.C.
- Comdr. Joseph Snyder - Pacific Missile Range, California
- Comdr. S. Oliver - Sanford Naval Air Station, Florida
- Dr. W. W. Mutch - Naval Research Lab, Washington, D.C.
- Mr. George Hicks - ONR, St. Louis, Missouri
- Mr. Hugo Sheridan- BUWEPS, Washington D.C.
- Mr. J. J. Ball - BUWEPS, Washington, D.C.
- 20 U.S. Test pilots - Naval Air Test Center, Maryland
- Mr. J. Guglielmello - BUWEPS, Washington, D.C.
- Mr. J. F. Mudd - BUWEPS, Washington, D.C.
- Mr. C. Weizman - Office of Chief of Naval Operations, Washington, D.C.

United States Army
- Capt. W. Crouch - Army Aviation Board, Ft. Rucker, Alabama
- Mr. John Duffy - Army Aviation, HUMMRO, Ft. Rucker, Alabama
- Mr. Ben Hanamoto - Land Locomotion Lab, Detroit Arsenal

Department of Defense
- Mr. G. W. Blackburn, Washington, D.C.

United States Air Force
- Capt. J. A. Birl - Wright Patterson Air Force Base, Ohio
- Capt. J. D. Boren - Wright Patterson Air Force Base, Ohio
- Mr. Howard McGrath - Aeronautical Systems Division, Wright Patterson Air Force Base, Ohio
- Mr. John Henderson - Aeronautical Systems Division, Wright Patterson Air Force Base, Ohio
- Mr. A. Jeffers - Aeronautical Systems Division, Wright Patterson Air Force Base, Ohio

Government
- Dr. S. R. Mohler - FAA, Oklahoma City, Oklahoma
- Mr. Richard Bray - NASA, AMES
- Mr. Fred Drinkwater - NASA, AMES

b. Universities - Academic
- Dr. Robert Gotts, University of Kansas
- Mr. William Barr, University of Kansas
- Dr. G. N. Hoover, Ohio State University
- Mr. I. B. Roberts, Ohio State University
- Dr. R. K. Knapp, Wichita State University
- Dr. J. A. Stern, Washington University School of Medicine

c. International
- Mr. John Matthews, National Institute of Argriculture Engr. Bedford, England
- Dr. G. H. Byford, RAF - Institute of Aviation Medicine
- Dr. J. C. Guignard, RAF - Institute of Aviation Medicine
- Sqdn. Ldr. D. L. Francis, RCAF-HQ, Ontario, Canada
- Wing Comdr. A. W. Armstrong, Canadian Joint Staff, Washington, D.C.
- Wing Comdr. D. O. Coons, Canadian Joint Staff, Washington, D.C.

d. Research organizations; non-profit foundations
- Mr. W. J. Ruby, Cornell Aeronautical Labs
- Dr. Frank Pelton, Cornell Aeronautical Labs
- Dr. W. J. White, Cornell Aeronautical Labs

C. Symposium on Human Vibration Research

The Office of Naval Research and The Boeing Company, Wichita Division jointly sponsored a symposium on Human Vibration Research, 30 October through 1 November 1962 at Wichita, Kansas. Thirty-one participants representing a wide array of government and military agencies, aerospace, related industries and universities were present.

The symposium content emphasized problems of definition and control of the vibration environment, measurement of effects of vibration, protection for the human vibration test subject, communication and dissemination of vibration research results and directions for future vibration research.

A summary of the meeting and discussion by Dr. Henning von Gierke concluded the symposium.

A listing of the attendees and their affiliation in 1962 is included.

Mr. J. E. Beaupeurt	Human Factors Chief	The Boeing Company Wichita, Kansas
Mr. Paul M. Burris	Systems Simulation	The Boeing Company Wichita, Kansas
Dr. Raymond A. Lawn, M.D.	Aero Space Medical Unit	The Boeing Company Wichita, Kansas
Dr. Herbert Megel	Bioastronautics Section	The Boeing Company Seattle, Washington
Mr. Donald L. Parks	Research Engineer Human Factors Technology	The Boeing Company Seattle, Washington
Dr. James L. Salomon, M.D.	Medical Director	The Boeing Company Wichita, Kansas
Mr. Fred W. Snyder	Human Factors	The Boeing Company Wichita, Kansas
Mr. Robert W. Costin		Bostrom Research Labs Milwaukee, Wisconsin
Mr. Stanley Lippert	Aircraft Divsion Engineering Division	Douglas Aircraft Co. Inc. Long Beach, California
Mr. Howard Sherman		Grumman Aircraft Eng. Corp. Bethpage, L.I., New York
Dr. Carl Clark		The Martin Company Baltimore, Maryland

Mr. Keith R. McCloskey	Life Sciences	The Martin Company Baltimore, Maryland
Dr. George N. Hoover	Space & Information Systems Division	North American Aviation Downey, California
Dr. Richard J. Hornick	Space & Information Systems Division	North American Aviation Downey, California
Mr. Douglas M. Walton	Bioscience Unit	North American Aviation Los Angeles, California
Mr. Hubert C. Vykukal		NASA-Ames Research Center Moffett Field, California
Mr. Harris F. Scherer Jr.		NASA, Houston, Texas
Mr. William R. Brewster Jr.	Biotechnology & Human Research	NASA, Washington, D.C.
Dr. G. C. Tolhurst	Head, Physiological Psychology Branch	Office of Naval Research Department of Navy, Washington, D.C.
Dr. Julius M. Peters	Head, Psychological Research Group, Space Environment & Life Science Laboratory	Republic Aviation Corp. Farmingdale, New York
Dr. Marvin J. Herbert	Medical Research Laboratory	United States Army, Fort Knox, Kentucky
Dr. Randall M. Chambers	Aviation Medical Acceleration Laboratory	United States Naval Air Development Center, Johnsville, Pennsylvania
Dr. David E. Goldman Cdr. MSC, USN		United States Naval Medical Research Institute, Bethesda, Maryland
Dr. Kenneth F. Thomson		United States Naval Training Device Center, Sands Point, New York
Dr. John A. Stern	Professor of Medical Psychology	Washington University School of Medicine St. Louis, Missouri
Dr. Robert J. Teare	Department of Psychology	Wichita State University Wichita, Kansas

Dr. W. Dean Chiles	Behavioral Sciences Laboratory	Wright Patterson AFB, Dayton, Ohio
Neville P. Clarke Capt. USAF (VC)	Aerospace Medical Research Laboratory	Wright Patterson AFB Dayton, Ohio
Morris J. Mandel Capt. USAF (MC)	Aerospace Medical Research Laboratory	Wright Patterson AFB Dayton, Ohio
Dr. Henning E. von Gierke	Aerospace Medical Research Laboratory	Wright Patterson AFB Dayton, Ohio

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13. ABSTRACT

This report reviews ten years of research in whole-body, low frequency vertical vibration supported by both the Office of Naval Research and The Boeing Company, Wichita Division. The results of twelve studies are presented, five in which the objective was to define and quantify human subjective reactions to vibration and seven in which vibration was a baseline condition for evaluation of sensory-motor task performance.

Physical effects of vibration are discussed in terms of the relationship between frequency of vibration and body sensation.

Research areas requiring further study are introduced and directions in vibration research for the future are suggested.

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Human Vibration Research						

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